EMBEDDING INTEGRATED PRODUCT DEVELOPMENT WITHIN THE SYSTEMS ENGINEERING PROCESS

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Abstract: *Conceptually sound product design derives from focusing on what the product does before determining what the product is, with form following function. This focus is most effective when based on design for the product life cycle, recognizing the concurrent life-cycle factors of production, support, phaseout; and disposal. It invokes integrating and iterating synthesis, analysis, and evaluation. These essential considerations are germane to Engineering Design in Integrated Product Development (EDIProD) when addressed as part of the systems engineering process and linked to the business process of the firm. The purpose of this paper is to presents an overview of the embedded relationship of engineering design to these higher-level processes.*

1. INTRODUCTION

Engineering design methods are not an end in themselves. They must be effective in practice and operationally compatible with integrated product development. And, integrated product development should be compatible with systems engineering and the business processes of the firm.

On the tenth anniversary of the now well known Seminar on Engineering Design in Integrated Product Development (EDIProD), it is appropriate to consider the proper embedding of the paradigm between engineering design and the business processes of the firm. This paper demonstrates that systems engineering does provide the essential morphology for this embedding [1].

EDIProD 2006 is the fifth biennial Seminar. It is intended to focus on design methods that have proved their value in practice. It is also important that the methods are based on sound concepts, for only then can they be well understood and purposefully implemented. This intention relates the 2006 Seminar with that of 2002, which was held under the motto ‘Design Methods that Work’.

Numerous conferences on engineering design have stressed the importance of the design practice in industry for creating better and more competitive products. The question arises as to what extent research in engineering design has left its mark on the product realization process. Advancing this process is of benefit to the producer and the customer alike [2].

There have been many reports that academics as well as companies are not fully satisfied from the current situation. The reasons are complex. Perhaps one drawback is that many methods are too sophisticated and have to be significantly changed to suit real-life problems. Or a problem has to be significantly modified to suit the method. Too much modification may be troublesome and lead to false conclusions and solutions. It is anticipated that embedding the design problem within the systems engineering process will help resolve this dilemma.

2. SYSTEMS ENGINEERING

Systems engineering (SE) is a technologically based interdisciplinary process for bringing products, systems, and structures (human-made entities) into being. The overarching purpose of SE is to make the world better for people. Accordingly, human-made entities should be purposely designed to satisfy human needs and/or objectives effectively while minimizing system life-cycle cost, as well as the intangible costs of ecological and societal impacts [3] [4].

Organization, humankind’s most important innovation, is the time-tested means for bringing human-made entities into being. While the main focus is nominally on the entities themselves, systems engineering embraces a better strategy. SE concentrates on *what the entities do* before determining *what the entities are*. That is, instead of offering products, systems, or structures per se, the focus of the organization shifts to designing, delivering, and sustaining functionality, a capability, or a solution.

Legions of academicians and practicing professionals are developing and applying powerful tools for analysis, experimentation, modeling, simulation, etc. to the domain of operations. These individuals represent the fields of engineering management, industrial engineering, management science, operations research, systems analysis, and others. Too often the efforts of these individuals are mistakenly called "systems engineering". These important tools and fields are necessary but not sufficient. Systems engineering is process and synthesis centered, and depends on and all of the above for its effective execution.

Entirely too much engineering time and talent is being expended addressing operational deficiencies plaguing the human-made world. Operational problem mitigation will always be needed, but the dramatic payoff for humankind lies in operational problem avoidance through system thinking.

3. THE ENGINEERED SYSTEM

Human-made or engineered products, systems, and structures are the central focus in this paper. Accordingly, this section and the material that follows pertain to the organized technological activities for bringing engineered products and systems into being. To begin on solid ground, it is essential that an appropriate comprehensive definition of the human-made, or engineered system, be presented.

3.1. Defining the Engineered System

Human-made, technical, or *engineered* systems are not easy to define in a rigorous way, as are systems in general. Engineered systems may be recognized by the following characteristics:

1. They have a *functional purpose* in response to an identified *need* and have the ability to achieve some stated *operational objective*.
2. They are *brought into being* and *operate* over a life cycle, beginning with a need and ending with phase-out and disposal.
3. They are composed of a *combination of resources*, such as humans, information, software, materials, equipment, facilities, and money.
4. They are composed of *subsystems* and related *components* that *interact* with each other to produce the system response or behavior.
5. They are part of a *hierarchy* and are influenced by external factors from larger systems of which they are a part.
6. They are *embedded* into the natural world and *interact* with it in desirable as well as undesirable ways.

Engineering has always been concerned with the economical use of limited resources for the benefit of people. The purpose of engineering activities of design and analysis is to determine how physical factors may be altered to create the most utility for the least cost, in terms of product cost, product service cost, and social cost. Viewed in this context, engineering must be practiced in an expanded way, with engineering of the system placed ahead of concern for components thereof.

3.2. Engineering the Product System

Commercial firms generally do not have an effective procedure in place for allocating scarce resources to product development. Most of the managerial, engineering, and design effort is directed to individual products. There is usually little formal attention given to the competition for development resources among products as they go through the design and utilization phases of their life cycles. This deficiency was addressed by this author during EDIProD 2004 [5].

A product, for example, may be a home entertainment center, a kitchen appliance, an automobile, a bridge, a building structure, or an aircraft. The product may be a consumable (a loaf of bread, a toaster, a cleaning product, a toothbrush, or lubricants) or a repairable (a lawn mower, an automobile, or a machine tool). Sometimes the repairable product is called *prime equipment* when it serves a larger system purpose (to place ordnance on target, or to move the freight). Finally, there are instances where the product is the system. An air traffic control system is one example; its purpose is to convert air traffic disorder and chaos into orderly traffic flow.

In general, classical engineering considers the main objective to be product (or prime equipment) performance, rather than the design and development of the overall system of which the product or equipment is a part. A product cannot come into being and be sustained without a production or construction capability and without maintenance and support, etc. Therefore, engineering the product system requires an interdisciplinary approach embracing both the product and associated capabilities for production or construction, product and production system maintenance, and phase-out and disposal.

Products, systems, and structures and designed, developed, deployed, and phased out in accordance with processes that are not as well understood as they might be. The cost-effectiveness of the resulting technical entities can be enhanced by placing emphasis on the following:

1. Improving methods for defining product and system requirements as they relate to true customer needs. This should be done early in the design phase, along with a determination of performance, effectiveness, and related system characteristics.
2. Addressing the total system with all of its elements from a life-cycle perspective, and from the product or prime equipment to its elements of support. This means defining the system in functional terms before specifying system elements of hardware, firmware, software, people, facilities, information, or combinations thereof.
3. Considering the overall system hierarchy and interactions between various levels in that hierarchy. This includes intra-relationships among system elements and interrelationships between higher and lower levels within the system.
4. Organizing and integrating the necessary engineering and related disciplines into the main systems engineering effort in a timely concurrent manner.
5. Establishing a disciplined approach with appropriate review, evaluation, and feedback provisions to insure orderly and efficient progress from the initial identification of need through phase-out and disposal.

As a point of emphasis, a system must respond to an identified *functional need*. Thus, the elements of a system must include not only those items that relate directly to the accomplishment of a given use or mission profile, but must also include maintenance and logistics support..

3.2. Engineering for Product Competitiveness

Product competitiveness is desired by both commercial producers and public-sector organizations worldwide. It is the product, or consumer good, that must meet customer expectations. Accordingly, the integrated product development challenge is to bring products and systems into being that meet these expectations cost-effectively.

Because of intensifying international competition, producers are seeking ways to gain a sustainable competitive advantage in the global marketplace. Acquisitions, mergers, and extensive advertising seem unable to create the intrinsic wealth and good will so essential for the long-term business health of the organization. Economic competitiveness is essential. Engineering design with an emphasis on economic competitiveness must become coequal with concerns for advertising, finance, production, and the like.

All other factors being equal, people will meet their needs by purchasing products and services that offer the highest value-cost ratio, subjectively evaluated. This ratio can be increased by giving more attention to the resource-constrained world within which engineering is practiced. To ensure economic competitiveness regarding the end item, engineering must become more closely associated with economics and economic feasibility. This is best accomplished through a life-cycle approach to engineering as presented next.

4. LIFE-CYCLE NGINEERING

Experience in recent decades indicates that a properly functioning product or system that is competitive cannot be achieved through efforts applied largely after it comes into being. Accordingly, it is essential that engineers be sensitive to utilization outcomes during the early stages of system design and development, and that they assume the responsibility for *life-cycle engineering* that has been largely neglected in the past. Thinking about the end before the beginning, per da Vinci philosophy, is highly recommended.

4.1. Product and System Life Cycles

Fundamental to the application of integrated product development is an understanding of the product life-cycle as illustrated in Figure 1. The life cycle begins with the identification of a need and extends through conceptual and preliminary design, detail design and development, production and/or construction, product utilization, phase-out, and disposal. The program phases are classified as *acquisition* and *utilization* to recognize producer and customer activities.

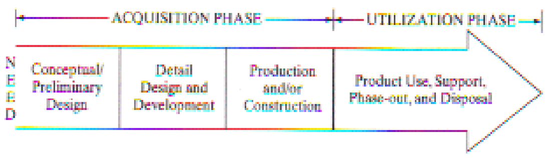

Figure 1. *The product life cycle.*

System life-cycle engineering goes beyond the product life cycle. It must simultaneously embrace the life cycle of the manufacturing process, the life cycle of the maintenance and support capability, and the life cycle of the phase-out and disposal process. Actually, there are four concurrent life cycles progressing in parallel as is illustrated in Figure 2 This conceptualization is the basis for *concurrent engineering.*

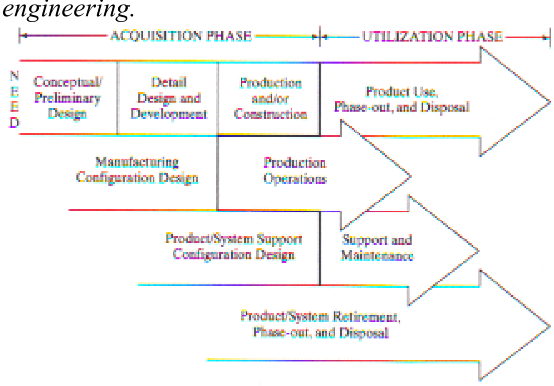

Figure 2. *Concurrent life cycles.*

The need for the product comes into focus first. This recognition initiates conceptual design to meet the need. Then, during conceptual design of the product, consideration should simultaneously be given to its production. This gives rise to a parallel life cycle for bringing a manufacturing capability into being. It encompasses many production-related activities to prepare for manufacturing.

Also shown in Figure 2 is another life cycle of great importance, which is often neglected until product and production design is completed. This is the life cycle for the maintenance and logistic support activities needed to service the product during use and to support the manufacturing capability during its duty cycle. Logistic and maintenance requirements planning should begin during product conceptual design in a coordinated manner.

A final life cycle should be initiated concurrently to integrate system design features that will ease phase-out and disposal. To the extent possible, life-cycle thinking should invoke end-of-life considerations for recyclability, reusability, and disposability.

4.2. Designing for the Life Cycle

Design within the system life-cycle context is different from design in the ordinary sense. Life-cycle focused design is simultaneously responsive to customer needs (i.e., to requirements expressed in functional terms) and to life-cycle outcomes [6].

Design should not only transform a need into a product/system configuration, but should ensure the design's compatibility with related physical and functional requirements. Further, it should consider operational outcomes expressed as producibility, reliability, maintainability, usability, supportability, serviceability, disposability, and others, as well as performance, effectiveness, and affordability.

The communication and coordination needed to design and develop the product, the production capability, the system support capability, and the phase-out and disposal capability, in a coordinated manner, is not easy to achieve. Progress in this area is facilitated by new technologies that make more timely acquisition and the use of design information possible. Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) technology are only two of these. Others are being developed which can integrate relevant design and development activities over the entire life cycle.

Concern for the entire *life cycle* is strong within the U.S. Department of Defense (DOD). This may be attributed to the fact that acquired defense systems are owned, operated, and maintained by the DOD. This is unlike the situation most often encountered in the private sector, where the consumer or user is usually not the producer. Those private firms serving as defense contractors are obliged to design and develop in accordance with DOD directives, specifications, and standards. Because the DOD is the customer and also the user of the resulting system, considerable intervention occurs during the acquisition phase.

Many firms that produce for private-sector markets have chosen to design with the life cycle in mind. For example, design for energy efficiency is now common in appliances like water heaters and air conditioners. Fuel efficiency is a required design characteristic for many automobile models. Some truck manufacturers promise that life-cycle maintenance requirements will be within limits.

These developments are commendable, but they often do not go far enough. When the producer is not the consumer, it is less likely that potential operational problems will be addressed during development. Undesirable outcomes too often end up as problems for the user of the product instead of the producer.

5. SYSTEM SYNTHESIS, ANALYSIS, AND EVALUATION

System design is the backbone of systems engineering, with system design evaluation being its compass. System design requires both integration and iteration, invoking a process that coordinates synthesis, analysis, and evaluation. It is essential that

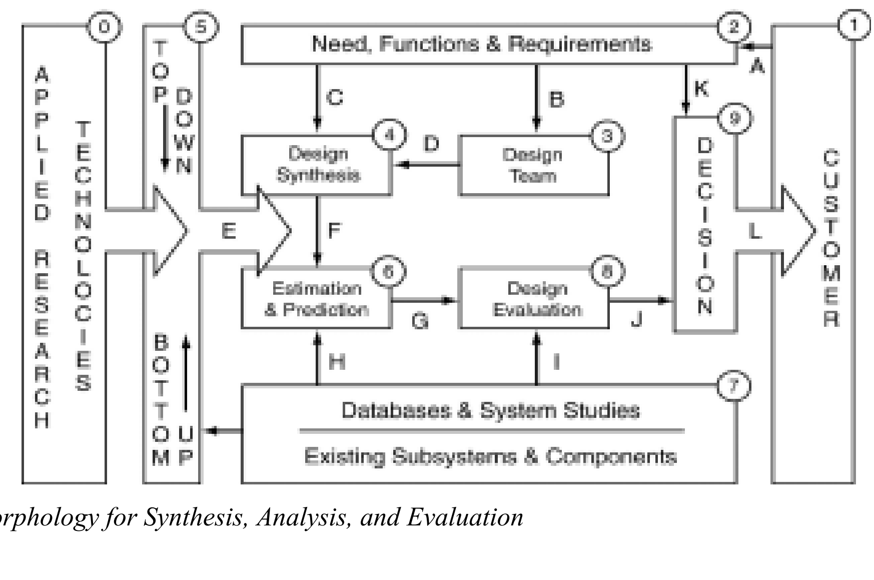

Figure 3. *A Morphology for Synthesis, Analysis, and Evaluation*

the technological activities of synthesis, analysis, and evaluation be integrated and applied iteratively and continuously over the life cycle in the true spirit of integrated product development. The benefits of continuous improvement in system design are more likely to be captured thereby [7].

Figure 3 exhibits a high-level schematic of the systems engineering process from a product realization perspective. It is a morphology for linking applied research and technologies (Block 0) to customer needs (Block 1). It also provides a structure for visualizing the technological activities of synthesis, analysis, and evaluation. Each of these activities is summarized in the paragraphs that follow, with reference to relevant blocks within the morphology.

5.1. Synthesis

To design is to synthesize, project, and propose what might be for a specific set of customer requirements, normally expressed in functional terms (Block 2). Synthesis is the creative process of putting known things together into new and more useful combinations. Meeting a need in compliance with customer requirements is the objective of design synthesis.

The primary elements enabling design synthesis are the design team (Block 3) supported by traditional and computer-based tools for design synthesis (Block 4). Design synthesis is best accomplished by combining top-down and bottom-up activities (Block 5). Existing and newly developed components, parts, and subsystems are then integrated to generate candidate system designs for analysis and evaluation.

5.2. Analysis

Analysis of candidate system or product designs is a necessary but not sufficient ingredient in system design evaluation. It involves the functions of estimation and prediction of design-dependent parameter (DDP) values (TPMs) (Block 6) and the forecasting of design-independent parameter (DIP) values from information found in physical and economic databases (Block 7).

Systems analysis and operations research provides a step on the way to system design evaluation, but adaptation of the models and techniques to the domain of design is required. The adaptation explicitly recognizes DDPs and embraces customer requirements.

5.3. Evaluation

Each candidate design (or design alternative) should be evaluated against other candidates and checked for compliance with the customer's requirements. Evaluation of each candidate in Block 8 is accomplished after receiving DDP values for the candidate from Block 6. It is the specific values for DDPs that differentiate (or instance) candidate designs.

Design-independent parameter (DIP) values determined in Block 7 are externalities. They apply across all candidate designs being presented for evaluation. Each candidate is optimized in Block 8 before being presented for design decision. (Block 9). It is in Block 9 that the best candidate is sought. The preferred choice is subjective and should be made by the customer.

5.4. Discussion of the Ten-Block Morphology

This section presents a discussion of the functions accomplished by each block in the system design morphology that was exhibited in Figure 3. The discussion will be at a greater level of detail than the description of synthesis, analysis, and evaluation previously discussed.

5.4.1. The Technologies (Block 0)

Technologies are the product of applied research as indicated in Block 0. They evolve from the activities of engineering research and development and are available to be considered for incorporation into candidate system designs. As a driving force, technologies are the most potent ingredient for advancing the capabilities of systems, products, and structures.

It is the responsibility of the designer/producer to propose and help the customer understand what might be for each technological choice. Those producers able to articulate and deliver appropriate technological solutions on time and within budget will attain and retain a competitive edge in the global marketplace.

5.4.2. The Customer (Block 1)

The purpose of system design is to satisfy customer (and stakeholder) needs and expectations. This must be with the full realization that the success of a particular design is ultimately determined by the customer, identified in Block 1.

During the design process, all functions to be provided and all requirements to be satisfied should be determined from the perspective of the customer, or the customer’s representative. Stakeholder and any other special interests should also be included in the “voice of the customer” in a way that reflects all needs and concerns. Included among these must be ecological and human impacts. Arrow A represents the elicitation of customer needs, desired functionality, and requirements.

5.4.3. Need, Functions, and Requirements (Block 2)

The purpose of this block is to gather and specify the behavior of the product or system in functional terms. A market study identifies a need, an opportunity, or a deficiency. From the need comes a definition of the basic requirements, often in functional terms. Requirements are the input for design and operational criteria, and criteria are the basis for the evaluation of candidate system and product configurations.

At this point, the product or system should be defined by its function, not its form. Arrow A indicates customer inputs that define need, functionality, and operational requirements. Arrows B and C depict the translation and transfer of this information to the design process.

5.4.4. The Design Team (Block 3)

The design team should be organized to incorporate in-depth technical expertise, as well as a broader systems view. Included must be expertise in each of the product life-cycle phases and elements contained within the set of system requirements.

Balanced consideration should be present for each phase of the design. Included would be the satisfaction of intended purpose, followed by producibility, reliability, maintainability, disposability, environmental compliance, and others. Arrow B depicts requirements and design criteria being imposed on the design team and Arrow D indicates the teams contributed synthesis effort where need, functions, and requirements are the overarching consideration (Arrow C).

5.4.5. Design Synthesis (Block 4)

To design is to project and propose what might be. Design synthesis is a creative activity that relies on the knowledge of experts about the state of the art as well as the state of technology. From this knowledge, a number of feasible design alternatives are fashioned and presented for analysis. Depending upon the phase of the product life cycle, the synthesis can be in conceptual, preliminary, or detailed form.

The candidate design is driven by both a top-down functional decomposition and a bottom-up combinatorial approach utilizing available system elements through Block 5. Arrow E represents a blending of these approaches. Adequate definition of each design alternative must be obtained to allow for life-cycle analysis in view of the requirements. Arrow F highlights this definition process as it pertains to the passing of candidate design alternatives to design analysis in Block 6.

Alternatives should be presented for analysis even though there is little likelihood that they will prove to be feasible. It is better to consider many alternatives than to overlook one that may be very good. Alternatives not considered cannot be adopted, no matter how desirable they may have proven to be.

5.4.6. Top Down and Bottom Up (Block 5)

Traditional engineering design methodology is based on a bottom-up approach. Starting with a set of defined elements, designers synthesize the product by finding the most appropriate combination of elements. The bottom-up process is iterative with the number of iterations determined by the creativity and skill of the design team, as well as by the complexity of the system design.

A top-down approach to design is inherent within systems engineering. Starting with requirements for the external behavior of any component of the system (in terms of the function provided by that component), that behavior is then decomposed. These decomposed functional behaviors are then described in more detail and made specific through an analysis process. Then, the appropriateness of the choice of functional components is verified by synthesizing the original entity.

Most systems and products are realized through a combination of the top-down and bottom-up approaches, with the best mix being largely a matter of judgment and experience. Arrow F represents the output of candidate designs made ready for analysis.

5.4.7. Estimation and Prediction (Block 6)

Cost and effectiveness measures are generated during estimation and prediction, using models and database information, to obtain design-dependent parameter (DDP) values (or TPMs) for each design alternative (Block 6). These models and simulations are based on physical laws, assumptions, and empirical data.

The DDP values provide the basis for comparing system designs against input criteria to determine the relative merit of each candidate. Arrow H represents input from the available databases and from relevant studies.

5.4.8. Physical and Economic Databases (Block 7)

Block 7 provides a resource for the design process, rather than being an actual step in the process flow. At this point, design-independent parameter (DIP) values are determined and provided to the activity of design evaluation, as represented by Arrow I.

There exists a body of knowledge and information that engineers, economists, and technologists rely on to perform the tasks of analysis and evaluation. This knowledge consists of physical laws, empirical data, price information, economic forecasts, and other studies and models.

Block 7 also includes descriptions of existing system components, parts, and subsystems. It is important to use existing databases in doing analysis and synthesis to avoid duplication of effort. This body of knowledge and experience can be utilized both formally and informally in performing needed studies, as well as in supporting the decisions yet to follow.

5.4.9. Design Evaluation (Block 8)

Design evaluation is an essential activity within system and product design and the systems engineering process. It should be embedded appropriately within the process and then pursued continuously as product design and development progresses.

Life-cycle cost is one basis for comparing alternative designs that otherwise meet minimum requirements under performance criteria. The life-cycle cost of each alternative is determined based on the activity of estimation and prediction just completed. Arrow J indicates the passing of the evaluated candidates to the decision process. The selection of preferred alternative(s) can only be made after the life-cycle cost analysis is completed and after effectiveness measures are defined and applied.

5.4.10. Design Decision (Block 9)

Given the variety of customer needs and perceptions as collected in Block 2, choosing a preferred alternative is not just the simple task of picking the least expensive design. Input criteria, derived from customer and product requirements, are represented by Arrow K and by the DDP values and life-cycle costs indicated by Arrow J. The customer or decision maker must now trade off life-cycle cost against effectiveness criteria subjectively. The result is the identification of one or more preferred alternatives that can be used to take the design process to the next level of detail. Alternatives must ultimately be judged by the customer. Accordingly, Arrow L depicts the passing of evaluated candidate designs to the customer for review and decision.

Alternatives that are found to be unacceptable in performance can be either discarded or reworked and new alternatives created. Alternatives that meet all, or the most important, performance criteria can then be evaluated based on estimations and predictions of DDP values, along with an assessment of risk.

Within the context of synthesis, analysis, and evaluation is the opportunity to implement systems engineering over the life cycle in measured ways that can help ensure its effectiveness.

6. SUMMARY AND CONCLUSIONS

The engineered or technical system is to be brought into being; it is a system destined to become part of the human-made world. Therefore, the definition and description of the engineered system is given early in this paper. It narrows the conceptualization of systems set forth in Sections 2 and 3. In most cases, there is a product coexistent with or within the system, and in others the system is the product. But in either case, there must exist a human need to be met. Since product competitiveness in the global arena is of keen interest to the producer, it is desirable to consider the product along with product production and/or construction, operations, support, phase-out, and disposal concurrently.

The product and system life cycle is the *enduring paradigm.* It is argued that the defense origin of this life-cycle paradigm has profitable applications in the private sector. The life cycle is first introduced with two simple diagrams; the first provides the product and the second gives an expanded concurrent life-cycle view.

Since design is the fundamental technical activity for both the product and the system, it is important to proceed with full knowledge of all system design considerations. The identification of design-dependent parameters and their counterparts, design-independent parameters, follow in the third figure.

From DDPs, there are technical performance measures to be predicted and/or estimated. The deviation or difference between TPMs and customer-specified criteria provides the basis for design improvement through iteration, with the expectation of convergence to a preferred design.

The explanation is enhanced by the development and presentation of a ten-block morphology for synthesis, analysis, and evaluation. It is here that one finds the most complete embedding of integrated product development into the systems engineering process.

Finally, a Polish translation of some of the ideas and concepts in this paper is available from the Polish Academy of Sciences. [8].

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