Innovative Practices in Product Development

Through the Eyes of a Product Developer

AK Chakrabarti

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Ministry of Defence, New Delhi - 1100 11

Product development, a science and an art, is carried out with a sense of proportion by an innovative and curious mind. Innovation is a lengthy process of transforming an idea into a product, into business for the creation of wealth, and for the welfare of the organisation, people, society, and mother earth.

Bhagavat Gita preaches knowledge is supreme. Aristotle called it Sophia, wisdom concerning universal truth.
Other Aristotelian virtues of thoughts are 'techne,' a state of capacity to make,'epistome'- giving shape to a theoretical knowledge, 'poiesis' - action to transform, 'praxis' - a practice, 'phronesis' - enhancing the quality of life.
Leonardo da Vinci is the symbol of innovation and diversity.
A product developer combines all the above to create a product that serves the cause of humanity and the globe.

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Dedicate to my Parents

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Preamble

THE WHOLE IS GREATER THAN THE SUM OF ITS PARTS

Aristotle (382-322 BC), the great Greek philosopher and polymath, coined the phrase. The inner meaning of this phase describes the basic foundation of any human endeavour. And that includes product development. The whole is greater than the sum of its parts by a factor, say X. This 'X' factor determines the efficacy of the whole for the purpose it is intended. Identifying the elements of the 'X' factor and finding means to accomplish them have been the sole objectives of product developers for many years. Many great thinkers contributed substantially wth several new concepts and techniques for a wholesome approach to product design. This book was written on this basic premise.

GET CONNECTED TO THE BIG: DESIGN SCIENCE APPROACH

Design is an act of creation. The product development community is bestowed with the opportunity and power to create. Every living species is intelligent. In the early years of human civilisation, various tools were made for survival. Later, several mechanisms were developed to help perform difficult tasks. And much later in the 12th century, the term engine appeared to describe war equipment. The word engine originated from the Latin *ingenium*. In the 18th century, it meant a device that converts energy into mechanical power and finally, in the 19th century, the revolutionary *Steam Engine* was invented. The community that developed such equipment was called the Engineers (Latin *ingeniare*).

Human civilisation progressed rapidly with various devices and equipment developed by engineers. But unfortunately, some of the equipment that was developed for self defence became the tools of aggression and destruction. Product developers used scientific principles increasingly to develop new products that created a market. Indiscriminate use of technology to earn profits caused serious irreparable damages to the environment – a huge concern for the generations to come.

Product development in the 21st century is highly challenging. The product developers have to respond to the market call for a ***faster, better, and cheaper*** product. Concern for environmental degradation, and being compliant with the current and emerging rules and regulations are also issues that need to be addressed adequately. In addition, the product developers have to transmit their knowledge of modern techniques and practices to a large section of the product development community for the welfare of the mankind and globe. ***The product developers need to see a much bigger picture***. The Toyota family has made a seminal contribution to propagating Toyota Production System which is now an industry standard.

Many great thinkers and philosophers thought of these bigger pictures over the centuries and spread their teachings in various ways. Though there are disagreements between them on certain issues, the core philosophies of these pioneers set the process of a new wave of thinking within the product development community. The common factors of these great thinkers are the urge to visualise the bigger picture for the welfare of mankind and the globe.

Aristotle, the *Father of Logic*, encouraged asking questions, arguments, and brainstorming to resolve social and scientific issues. The Aristotelian virtues of thoughts: *techne* (a state of capacity to make), *epistome* (giving shape to a theoretical knowledge), *poiesis* (action to transform), *praxis* (a practice), *phronesis* (enhancing quality of life) are still the foundation of modern product development.

Centuries later, Francis Bacon (1561-1628), English philosopher and statesman, and Rene Descarte (1596-1650), French philosopher, mathematician, and scientist stressed the importance of cultivating scientific methods to develop knowledge and gain the power to understand the mother nature to promote human welfare.

In ancient Indian philosophy, the word Sacchidanada was used to define the ultimate unchanging reality. The compounded Sanskrit word consists of three words – *Sat, Chit. and Ananda*. Sat means being, existence, and true. Chit means consciousness. Ananda means bliss. Similar to this ancient Indian philosophy, a new concept was originated by Alan R. Hevner to describe the spread of Design Science Research in a 3 cycle view (Rigor- knowledge, Relevance–system, Design cycle) presenting a bigger picture.

Sometime around the mid-20th Century Buckminister Fuller, an American designer, inventor, and author introduced the concept of ***Design Science*** to perform engineering design in a systematic form. Fuller cautioned about the scarce global resources which need to be consumed judiciously. He stressed upon the innovative instinct of the product developers to 'do more and more from less and less.'

In modern times, we need to appreciate many brilliant minds who introduced revolutionary concepts in product development. Leading amongst them is Elon Musk, known for his contribution to electric mobility and space launches. Space X, a company of Musk, has successfully demonstrated the recovery of the first-stage booster of the Falcon 9 rocket on a sea-based platform. A single recovered stage has already been reflown more than ten times with routine inspection and clean-up and is expected to fly many more times with refurbishment. The first stage of a large space rocket cost about 70 % of the launch vehicle cost. Reusing the first stage many times will bring down the cost of space launch drastically (experts feel about one-tenth).

Remaining focussed on the task at hand is surely advisable, but seeing the bigger picture for the wholesome benefit of society makes a team ***Champion***, as demonstrated by Elon Musk. This is the moral of ***Design Science***.

THERE IS A SIMPLE WAY TO SOLVE A COMPLEX PROBLEM

This is a unanimous agreement with the statement "*For every complex problem there is an answer that is clear, simple, and wrong*", made by H.L. Mencken, American Journalist, and Free

Thinker. The word ‘wrong’ in the statement created confusion, and many felt that the answer wrong is not an answer at all. However, it is commonly observed that every complex problem has a simple solution. This book is written with that premise.

Many products are technologically overly complex. Designers have solved difficult problems with years of dedicated work in design, fabrication, evaluation, and testing. In most cases, it was iterative. Researchers in product development attempted to find out a well-structured and systematic approach to solving complex problems. As a result, many new concepts and techniques emerged.

An attempt is made in this book to compile all modern thoughts, principles, and techniques in product development. A few new concepts are also introduced. The reader's concern to search five hundred pages in this book for a simple solution to a complex design problem is valid. For the benefit of the design teams, the product design is presented in 11 well-defined ***Process Steps***. Indeed, all the steps may not be relevant for every design exercise. The reader can select the appropriate steps that meet the requirement.

The design exercise can broadly be described with 5 Essentials, which will help find the ‘simple’ solution to complex design problems: Goal, Context, Design Space, Design Drivers, and Criticalities The design team can frame the relevant question to describe these essential factors and keep the questions alive until completion of the development process. The book helps find suitable techniques and tools to solve the design problem. The design methods are presented in well-defined process steps to ensure the design progresses on the right track. The result of each process step needs to be properly documented and made available to the stakeholders.

Finally, the book is written on the premise that a disciplined and systematic approach contributes significantly to innovative product design.

Acknowledgement

After spending four decades in the design and development of high-end military systems, I was often baffled by the question - *could it have been better*. I believed that most of the designers' efforts were based on instinct and judgement, though often influenced by the conservative philosophy - 'if works, don't change'. After I retired from active services, I had plenty of free time to read books on the history of science and technology. The first book that I read was amazing, *The Idea Factory* – an excellent narration on research programmes at Bell labs, AT&T. This is a must-read for every scientist, engineer, and manager to know how basic research and product development can be judiciously mixed to develop revolutionary new technologies and products that could change the course of human civilisations. Scientists and engineers at the Bell lab won ten Nobel prizes. Another book, The Future of Design Methodology edited by Herbert Birkhofer opened up my entry into the world of design sciences.

21st Century design paradigm is *Faster, Cheaper, and Better*. A huge volume of research work has been carried out by researchers in design science and methodologies in the past few decades. Practically, a product designer can't study and apply various design philosophies, concepts, and methodologies on day-to-day basis. Neither such concept is commonly taught in the academic curriculum. I felt an urgent need to compile modern design philosophies, concepts, and methodologies into well-defined process steps to help the product designer progress the design exercise in a systematic and disciplined manner. Thus, the idea of writing this book originated.

I was overwhelmed by the story of the *Quality Movement* in Japan that was, interestingly, spearheaded by the American specialists Edwards Deming and Joseph Juran with active support from the Union of Japanese Scientists and Engineers (JUSE). Genechi Taguchi, Kaoru Ishikawa, C.R. Rao, and Kiichiro Toyoda inspired product developers with new concepts and techniques. Japan proved that the phenomenal economic growth for the nation can be achieved through producing high-quality products.

Buckminister Fuller, the originator of Design Science concepts and remembered for the geodesic dome, reminds the 21st Century product designers about the importance of scarce resources of the globe which need to be used judiciously considering the needs of the generations to come. His most valued words - *doing more and more with less and less* should always reverberate in the designers' minds while taking up new assignments. Exhaustive modelling, simulation, and optimisations are the needs of the hour.

The 20th Century is surely the dream century in product development. Many thinkers and researchers made brilliant contributions to the Science of Product Design and Development. Notable among them are Genrich Altshuller (TRIZ), Nam P Suh (axiomatic design), Walter

Shewhart (statistical quality control), HAWatson (fault tree analysis), Philip Crosby (zero defect), Bill Smith (6-sigma), and John Krafcik (lean system). Most of these concepts are developed further and used regularly by product designers. I was motivated by the seminal works of these accomplished thinkers.

Working under tutelage with Dr APJ Abdul Kalam, former President of India, and legendary product developer and technology leader had been a great opportunity for me. We learnt from him the importance of various organisational and human values in product development, stepping out of our guarded compartments to work as a team with a seamless flow of information, brainstorming, and peer reviews. I was inspired a lot by the thoughts and vision of Dr Kalam to write this book.

Dr VK Saraswat, Member, NITI Aayog and Chancellor, Jawaharlal Nehru University, my long-time colleague, friend, and superior in DRDO suggested to compile my thoughts on product development. My fragmented thoughts inspired me to learn more about the latest concepts and techniques of product development. I was amazed to know about the depth of research carried out in product development. I thought of compiling all I learnt in form of a book. I am thankful to Dr Saraswat.

I always felt that sometime very simple philosophies that we learn from our mentors and peers remain as tacit knowledge throughout the professional career. I worked under Major General R Swaminathan at my formative years in DRDL. He had a caption in his office cabin defining *engineer is one who can do a job in one penny what others will do the same in one pound*. I can't remember the origin of the quote, but the message General Swaminathan delivered remained the most fundamental principle in all my endeavour. I was so delighted to learn very recently, and am sure everyone will feel the same, that Elon Musk is aiming to bring down the cost of satellite launch to $ 20 per 1 kg of payload hopefully by 2030 with Super Heavy Starship from 1990s cost of $ 18000 using Space Shuttle. I am indebted and grateful to General Swaminathan.

It may be pertinent to remind the product developers that System Engineering is always the foundation of all complex engineering products. I learnt a lot about system engineering from many colleagues in DRDO. I would like to fondly remember my association with Shri NV Kadam, Shri CR Prasad, Shri SS Misra, Dr SK Choudhury, Shri N Prabhakar, Shri KK Mangrulkar, Shri MSR Prasad, Shri A Jospeh, Shri Sangam Sinha, Shri VK Aggarwal, Shri Bikas Bhattacharya , Shri GAS Murthy, Shri B V Papa Rao, Dr AP Dash, Smt. Sarda Prabhakar, Shri R Krishna Rao and Dr Naresh Kumar. Their thoughts and works reflect in my writing. I thank them all profusely.

Shri BHVS Narayan Murthy, former Director General DRDO laboratories and senior DRDO scientists - Shri R Krishnamurthy and Shri JV Satyanarayana extended great support in reviewing the book thoroughly spending valuable time and offered useful comments and suggestions. I value their contribution and thank all of them. I thank my old colleagues in DRDL and especially Shri Rajiv Sarma for helping me with many articles and books and Mrs Ammu and Mrs Prathima for excellent secretarial support during my tenure in DRDL and in the conceptual phase of the book.

I consulted many experts from diverse fields. Discussing with Prof. Dibakar Das, Dean, Central University Hyderabad, and Dr Anup Kumar, professor in mechanical engineering JBIET, on various aspects of the Design of Experiments and ANOVA have been very fruitful. Prof Das, Dean of Hyderabad was kind in sharing the experimental results on ANOVA in the planarisation process for inclusion in the book. I convey my sincere thanks to Prof Dibakar Das and Prof Anup Kumar. I was greatly benefited discussing with Mr RC Chakrabarti, my senior colleague, in the areas of soft computing and through his website www.myreaders.info. I am thankful to him.

There are always great friends who motivates with encouraging words. Dr A Subhananda Rao, former Director HEMRL and my long-time friend and colleague encouraged me all along writing the book. Dr Debashis Mukherji, former DRDO scientist and faculty member at the Technische Universität Braunschweig, Germany, a family friend, inspired me a lot. I picked up few a thing from his recent book 'High – Temperature Materials for Gas Turbine Applications'. The book was released a few months back by DRDO. I convey heartfelt thanks to both my long-time friends.

I thank DRDO for extending the wonderful opportunity to express myself as a product developer and to share with generation next the things I learnt from great philosophers and thinkers. I am thankful to Dr Samir V Kamat, Chairman DRDO for scheduling the book release on 28th February, National Science Day – a day when the scientific community rededicate to the welfare of people and society through science and technology.

I am thankful to the DESIDOC, DRDO for the support and motivation to write the book. I thank heartily Dr K Nageswara Rao, Director, DESIDOC and Editor-in- Chief for extending helping hands with a large volume of valuable information and references without which it would have not been possible for me to write the book. I am thankful to Smt Alka Bansal for many useful interactions, information, and excellent editing. I appreciate the work done and convey my sincere thanks to all members of the DESIDOC team, especially to Shri Rakesh Kumar for regular coordination and interaction, Shri Rajesh Kumar for the innovative cover page design, Shri Rajesh Kumar Singh for printing, and Smt Khusbhoo and Smt Gunjan Bakshi for the editorial assistance.

This is my first book. It would have been impossible for me to work for long hours without constant encouragement from my wife Ruma, and the active participation of daughters Malini and Shreya in reviewing and discussing various aspects, especially the new concepts. I admire my family's contribution and thank all heartily.

I was inspired in my childhood towards building artifacts by my father who had excellent skills with mechanical tools and gadgets. I would consider my effort fruitful when the students and product developers get benefitted from various concepts, schemes, and methods presented in the book.

Hyderabad AK Chakrabarti

Product Development: Part I

Design Philosophy and Concepts

CHAPTER 1

Starting A New Design Assignment

"The childhood shows the man/As the morning shows the day." – the beautiful words from Paradise Regained by John Milton are the words to be always remembered by product developers. For a product developer, the early hours are important. In most cases, the excitement of starting something new and challenging may overshadow the need for a deeper inquiry into certain vital aspects of the programme. This is the phase where the journey begins and spreads, as Milton said in the following line "Be famous then/By wisdom, as thy empire must extend, So let extend thy mind o'er all the world/In knowledge, all things in it comprehend"

And thou thyself seem'st otherwise inclined
Than to a worldly crown, addicted more
To contemplation and profound dispute,
As by that early action may be judged,
When slipping from thy mother's eye thou went'st
Alone into the temple; there was found
Among the gravest rabbis disputant
On points and questions fitting Moses' chair,
Teaching, not taught; the childhood shows the man
As morning shows the day. Be famous then
By wisdom; as thy empire must extend,
So let extend thy mind o'er all the world,
In knowledge, all things in it comprehend

John Milton
(1608–1674)

The early phase of product development is hugely important as it opens the vast expanse engineering excellence by comprehending 'all things in it.' Two interesting points emerge:

- What are the 'all things'
- What we are going to achieve

The journey begins when the 'all things' are known, and the plan to execute the same is evolved. To the product developers, these two requirements are described as:

- System Context Diagram (all things)
- Goals and Targets (going to achieve)

1.1 SYSTEM CONTEXT

A new product must be characterised by its important attributes. It may be an incremental variation of the old one, scaling up, or completely different with new concepts and technologies. Depending upon the situation, the product developer plans the course of development. As the development work progresses, newer problems surface, which are addressed by the development teams. Sometimes surprises do occur, which cause disturbances in functioning. To avoid disruptions in the activities, it will be appropriate to examine the system for all relevant contexts early. Such analysis may help to set the goal and course of the developmental work.

The product's characteristics and context with the neighbouring systems need to be critically examined to evolve the development plan. The areas that may need critical scrutiny, research, or experimentation are identified in the context diagram, which significantly helps to set the goal.

The System Context Diagram, a simple presentation that all stakeholders including the top management understand, is presented in Fig. 1.1.

1.1.1 System Context Diagram

The functional requirements of a system should be integrated with all internal and external factors.

A typical System Context Diagram of an industrial product is shown in Fig. 1.1.

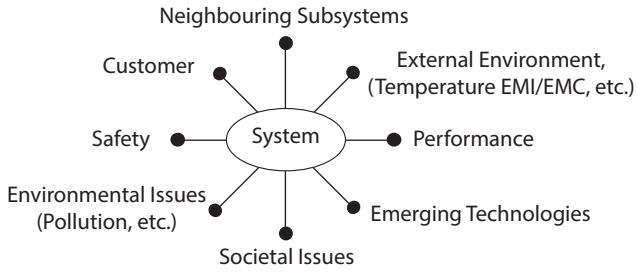

Figure 1.1. System Context Diagram (typical).

(a) Assigning Weightage

Each aspect of the Context Diagram can be analysed for its criticality. If the project goal is observed adversely influenced by some of the factors in the Context Diagram, necessary actions could be initiated at an early phase of the developmental programme.

A System Context Diagram is a simple but powerful tool. The weightage of various factors can be projected on this diagram for the benefit of the stakeholders. Sometimes, if the factor significance is not assessed correctly and recognised late, the programme is impacted adversely. A context diagram brings out the issues with clarity which may be highly relevant for decision-making. In Fig. 1.2, weightage (typical) on the factors has been assigned. It may be noted that societal and environmental factors (typically) were assigned higher weightage, which prompts two actions. Firstly, the issues are recognised at the organisational level, and necessary alerts are generated to comply with the current rules and regulations; possible changes are also considered. Secondly, the design team attempts to minimise the environmental impacts. The product issues are made transparent to all stakeholders and, if relevant, to the customer.

About the Monograph

21st Century Product Development have many challenges. Two major ones, though conflicting at times, are the market demand of Faster, Better and Cheaper product and to comply with societal and environmental requirements. That makes the product developer to think beyond the customers. Product developers should be concerned about preserving the scarce raw materials for generations to come. A complex Really New Product needs to be evaluated for two aspects as defined by Deep-Tech: designing innovatively with current technology and designing with emerging technology. Product developers must judiciously combine these two aspects to sustain the market competition. Researchers and thinkers in technology and product development have carried out extensive research since middle of last century to establish a philosophical foundation of exploitation of science and technology for the wholesome benefit to society and the globe.

The book is aimed to make to make the product developers aware of the historical and philosophical perspective in product development that are essential to develop a complex product. A good number of modern methodologies and techniques that are regularly used in the industry have been compiled. The product development process is described elaborately in well defined process steps in a sequence, named as Define-Configure-Connect- Design (DCCD). The philosophical thought process is embedded into the sequence. Certain essential aspects like uncertainty analysis, risk assessment and mitigation, failure analysis and forecasting are included in the sequence at appropriate locations. A set of modern quality tools is also presented.

The author has left enough scope for the designers to modify or design new sequence based on the complexity of the product and for the researcher to evolve new concepts to dovetail emerging technologies into the product configuration and design.

About the Author

Sh Amal Kumar Chakrabarti worked four decades in development of high-end aerospace products and systems. He is graduated in Mechanical Engineering from Jadavpur University and obtained post-graduation in Space Engineering and Rocketry from Birla Institute of Technology, Mesra. He joined DRDL in 1974 and superannuated as Director of DRDL in 2013.

He worked in the areas of rocket propulsion and control actuation system. For two decades he worked in project management and was leading major aerospace missions. He developed a new scheme, Bird's Nest Diagram, to establish intra system connectivity in a highly complex system. He is presently engaged in research in value-based products development and the philosophical aspects of engineering design and technology development.

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