

Addressing Problems by Systems Engineering Methods, Techniques, and Tools-Model Framework

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Abstract: Systems Engineering is an interdisciplinary and holistic discipline with methods and techniques to address complex problems. This paper proposes an integration of system life-cycle processes and stages from ISO/IEC 15288 with the proposed tools-model framework as a basic framework, allowing team to generate data, define customer needs, optimize solutions, architecture the system, make decisions, validate, analyze failures, and realize the system. This paper gives a short presentation of tools-model framework application on a real case in industry. The application of this proposed model led to a significant increase of the firm total and (labors, materials) partial productivity, quality-productivity index, profit, and value added almost by (39%, 65%, 20%, 39%, 202%, and 119%) respectively, noticeable positive decrease of defective products percentage, downtime, rework, and lead time almost by (79%, 28%, 98%, and 80%) respectively, also acquiring new customers and new products, besides developing training programs, and solving customer claims.

Keywords: Systems Engineering (SE), ISO/IEC 15288, systems engineering tools, Systems life-cycle integration, Systems Engineering Lifecycle-Tools-Model Framework (SELTMF)

INTRODUCTION

Systems Engineering (SE) is an interdisciplinary, collaborative approach to enable the realization of successful systems verifying a life-cycle balanced system solution which satisfies customer needs. SE treats the whole system and even its elements treating any thing as a system. The SE management is accomplished by the three activities; development phasing, SE process, and life-cycle integration. Terry and Frank [1] defined SE and determined seven tasks of SE: (State the problem, Investigate alternatives, Model the system, Integrate components, Launch the system, Assess performance, and Re-evaluation) explaining the seven phases of life-cycle in details and defined the purpose of SE as is to produce systems satisfy customers' needs, increase success probability, and reduce risk and total-life-cycle cost. Frank [2] explained that the need for SE is dependent on the size of the system under consideration, its complexity, its technological risk, and the needs of the customer in defense and in commercial practice. Clement and Susan [3] showed that SE encompasses the entire product life-cycle, including product conceptualization. They summarized the present state and future direction of SE research that one can leverage to most effectively support bid efforts. Russell [4] proposed a methodology to support non specialist end users in the identification, organization and discussion of information required to manage SoS evolution, and uses a modified form of Hazard and Operability Study (HAZOPS) to analyze the associated risks of evolution. Bogle et. al [5] applied the process SE techniques to biochemical processes taking into account an important role in batch biochemical processes for Computer Assisted Operation (CAO), i.e. planning of operations on a day-to-day bases using simulation tools. SE is the art and science of developing an operable system capable of meeting requirements within often opposed constraints. The analysis confirmed that the objectives of software engineering, the problems encountered managing it, and the techniques used to resolve those problems are essentially the same as those found in SE. So, Mark [6] showed the activities that are common to SE and software engineering. David [7] showed recurrence plots reveal long-term and emergent behavior in complex systems when specific criteria are met. This technique may be used in SE in such diverse areas as systems architecture to predict emergent behaviors in complex systems and program management to predict the long-term health of a complex project among others. In energy systems applications, Jamal et. al [8] Studied how SE methods can help address today's grand

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(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 12, December 2013

challenges, such as energy problem through defining problem by articulating the problem in its context as clearly as possible, Sharpening the problem further by transforming it into need statements and using SE modeling and analysis techniques to understand, communicate, debate, and facilitate decisions about complex problems and assessing potential solutions. Albert and John [9] described a novel approach through development of V-model for integrating manufacturing and supply chain considerations into the SE process applied for aerospace and defense industry through the cost of developing new generation of system continues to spiral out of control. Marianne and Gerrit [10] investigated the value of specific SE tools applied to the flow and storage of finished products included: context diagram, physical architecture, Integration Definition for Function Modeling (IDEF0) diagrams, Use Case Scenarios, Scenario Tracing and Geographical Model. As risk analysis and affordability, Quentin [11] used affordability as a decision making tool, which can be approved, measured and predicted. he provided analytical path from determining requirements to fielding affordable systems conducting research into the concepts of affordability and methods to implement the approach. He also established a foundation for creating affordability SE Sciences, he initiated research of complexity sciences to understand links between fitness and affordability, and also investigated game theoretical modeling and other advanced SE concepts to focus on thrusts. Hee et. al [12] used the SE approach to guide the development of a new business model-based design method using these tools though the project phases such as IDEF0 model, functional architecture, Strength, Weakness, Opportunity, Threats (SWOT) analysis, buyer utility map, fault analysis tree, pre-defined assessment system, Quality Function Deployment (QFD), and system analysis and control including trade-off studies, effectiveness analyses, risk management, configuration management, interface management, data management, and so on. By using SE, project success rates were enhanced from 16% to 28% in 2000. The design process for damage control support systems was based on SE process of ISO/IEC 15288, EIA/ANSI 632, and IEEE 1220. The International Standard, Systems Engineering Life Cycle Processes, (ISO/IEC 15288) [13] established a common framework for describing the life cycle of systems and defined a set of processes and stages. These processes can be applied at any level in the hierarchy of a system's structure to the whole life-cycle including conception, development, production, utilization, support and retirement of systems using tasks of defining customer needs, stating the system problems, investigating solutions, modeling the system of interest, managing functions interfaces, and assessment of the system to get a product or introduce a service. The life-cycle processes can be applied concurrently and iteratively to a system and its elements on any system. It therefore applies to one-of-a-kind, mass-produced, customized and adaptable systems or services systems. Department of Defence (DoD), NATO, Ministry of Defence (MoD), and National Aeronautics and Space Administration (NASA) all developed SE model frameworks and NATO has decided that ISO/IEC 15288 shall be the framework for Systems Life-Cycle Management (SLCM) [14]. NASA [15] has provided its own SE framework to be a general guidance and information on SE that will be useful to the NASA community. Tommy et. al [14] presented an example on how ISO/IEC 15288, Architectural Frameworks and Modeling and Simulation (M&S) can be integrated and the benefits of that integration, especially how M&S can be used to develop and execute system designs giving a presentation of some ideas concerning tool support such as MODAF with six viewpoints. The existing frameworks depended on one or more SE tools, however system life-cycle processes, stages can be integrated using a complete SE tools-model framework. So, the present paper introduces to ISO/IEC 15288 life-cycle processes and stages, aiming to present the proposed model framework of system life-cycle integration using support tools as the basic building blocks in this model. It presents how the life-cycle processes, stages, and tools can be integrated and the benefits of that integration, especially how SE tools can be used to present, model, develop and execute the system. It also assess this proposed model by applying it to a real industrial case to improve its system performance.

SYSTEMS ENGINEERING LIFE-CYCLE

The System Life-cycle Processes

The SE life-cycle processes are described in four process groups according to ISO/IEC 15288; Agreement Processes, Enterprise Processes, Project Processes, and Technical Processes [13]. These groups and their included processes are illustrated by Figure 1 Each group will be described very briefly in the following sections.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 12, December 2013

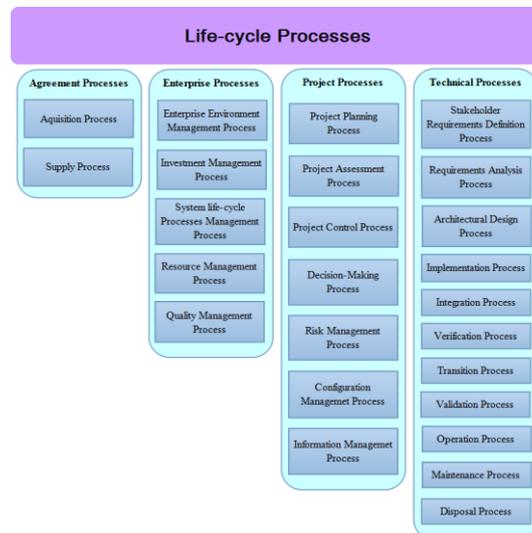


Fig. 1. Systems engineering life-cycle processes - ISO/IEC 15288

The System Life-Cycle Stages

The life cycle stages/phases - according to ISO/IEC 15288 - provide a framework for the detailed modeling of system life cycles using the system life cycle processes described above to model life cycles of the systems. Every system of interest (SOI) has its own life-cycle, that can be decomposed into a set of stages. An example of a life-cycle six stages [13], is shown in Figure 2.



Fig. 2. Life-cycle six stages - ISO/IEC 15288

The life cycle is partitioned into a system life-cycle period of time where each one period is represented by each stage and has a distinct purpose. The partitioning is practical since it is easier to work in small, understandable and timely steps.

ISO/IEC 15288 LIFE-CYCLE PROCESSES, PHASES, AND SE TOOLS INTEGRATION

Life cycle integration is necessary to ensure that the design solution is viable throughout the life of the system. It includes the planning associated with product and process development, as well as the integration of multiple functional concerns into the design and engineering process. In this manner, product cycle-times can be reduced, and the need for redesign and rework substantially reduced. Life cycle integration is achieved through integrated development—that is, concurrent consideration of all life cycle needs during the development process. Any system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce system-level results. The results include system-level qualities, properties, characteristics, functions, behavior, and performance, and so as to the SE methods and techniques. The most of the system life-cycle processes presented former are used to some extent during every stage of a system life-cycle that is executed by applying SE tools. Figure 3 roughly illustrates to what extent the process groups and tools are used in the different stages.

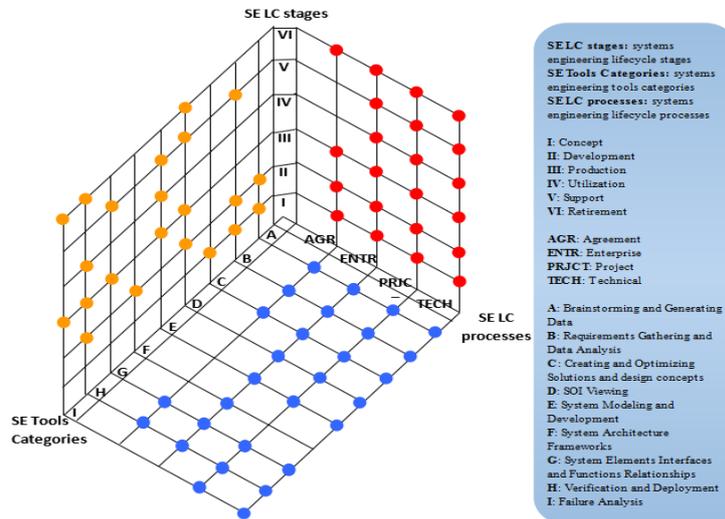


Fig. 3. An example matrix of life-cycle processes, stages, and proposed tools categories in relation matrix

A. The Systems Engineering Lifecycle-Tools-Model Framework

The system frameworks make it possible to describe and communicate systems within and between organizations, providing that, the same, or similar frameworks are used. Without a common language it is difficult to communicate. Systems Engineering Life-cycle Tools-Model Framework (SELTMF), provide guidelines regarding content and how to describe, solve, and present systems different issues into full system framework over its life-cycle; besides they provide guidance concerning how to design or implement a specific system or element, or how to develop or acquire systems not only using traditional steps but through architecture tooling framework. The proposed SELTMF is illustrated by Figure 4. SE tooling is used to identify capability needs, relate needs to systems development and integration, attain information interoperability and supportability, and therefore manage investments.

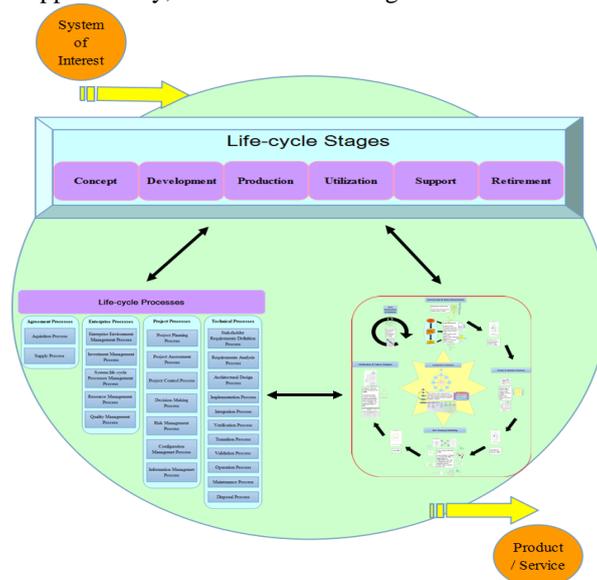


Fig. 4. System interaction with typical life-cycle processes and stages and SE tools as the basic building blocks

THE SYSTEMS ENGINEERING TOOLS

SE tools, will allow the team to generate and manage information, understand customer requirements, explore design options, optimize solutions, make decisions, validate, implement and realize the system, these tools could be

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 12, December 2013

mathematical, graphical, modeling, and architecture [16, 17, 18]. SE Tools demonstrate how using integrated or concurrent engineering methods, copiously illustrated with figures, charts, and graphs offering methods, frameworks, and techniques for designing, implementing, and managing systems exhibiting the effect of the SE concept and its importance during the design and development of a complex system.

A. *The Systems Engineering Tools Framework*

The efforts within the area of frameworks that we know of; the Incremental Commitment Spiral Model, Model Oriented Systems Engineering, Model Driven Architectures, Model-Based Systems Engineering, Department of Defense Architectural Framework, and Ministry of Defense Architectural Framework (ICSM, MOSES, MDA, MBSE, DoDAF, and MoDAF) all strives to create a common architecture framework for descriptions of system architectures [19, 20, 21, 22, 14, 23]. According to interpretations, the main goal with any model framework, is to support development and documentation, of the system, defining stakeholders and communicating between them. Systems frameworks may use one or more tool to demonstrate the system of interest. "Systems Engineering Tools Framework - SETF" map presents the tools application through the whole life-cycle of any system, the proposed tools for each level, and the application cycle over the life-cycle, that is illustrated by Figure 5. The tools are categorized into four main groups illustrating its utility and usage through the proposed SE model, these categories and tools utilization into the SE model are as follow:

- Architecture framework; is considered a general step in the tools-model framework and is the core of this framework. It is a way to viewing and defining an enterprise, providing a comprehensive approach for designing, planning, implementing, and governing an architecture.
- Defining requirements; gathering, defining, and analyzing data of customer or system requirements, where tools such as Affinity Diagram, Need Means Analysis, Viewpoint Analysis can be used during the system concept stage to state the system issues.
- Creating and optimizing solutions; investigating, exploring, and assessing existing development system and proposed solution alternatives using Function Means Analysis for example, and FFMEA to determine and prioritize failure modes.
- System viewing and modeling; to determine system reliability, presenting, and assessing system development and utilization it is needed to view this system using modeling tools such as V-model or IDEF.
- System verification and analysis; system supportability, testing, assessment, or failure analysis can be done using Quality Function Deployment or Fault tree Analysis and then get system feedback to reevaluate its solution concepts.

The Systems Engineering Tools Framework Application Examples

There are an increasing number of opportunities for systems engineers to make important contributions for manufacturing and services fields. The filed of application is a company, which is considered a subcontractor (tier) serving many companies in Egypt working in many fields such as vehicles (the biggest customer), plastics, electrical equipments, etc. This industry undergo some main stages in the manufacturing process as design, receiving raw materials, sheet metal cutting and pressing, plastic injection, assembly, treatment and painting, and finally delivering to customer. The SE is applied to this company considering it all as a system using SETF categories to present this system treating its issues.

1) *System architecture framework*: It is required to view the enterprise, design, plan, implement, and govern the enterprise architecture. In British Ministry of Defence Architecture Framework (MODAF), the problem space is split into manageable pieces, defined as views, which enables decision-makers to manage complexity. Each view has a particular purpose and the views are categorized under seven viewpoints, shown in Figure 6. Some of the views provide high level information about the system; whilst others describe specific aspects or relationships between different aspects of the system.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 12, December 2013

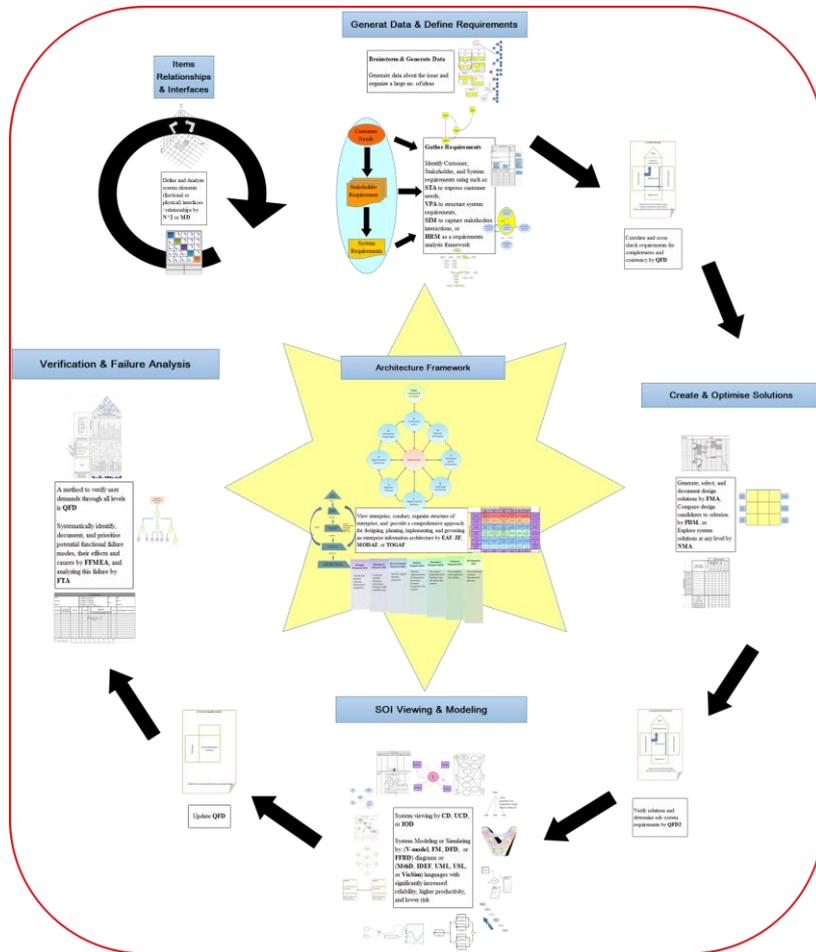


Fig. 5. Systems Engineering Tools-Model map cycle

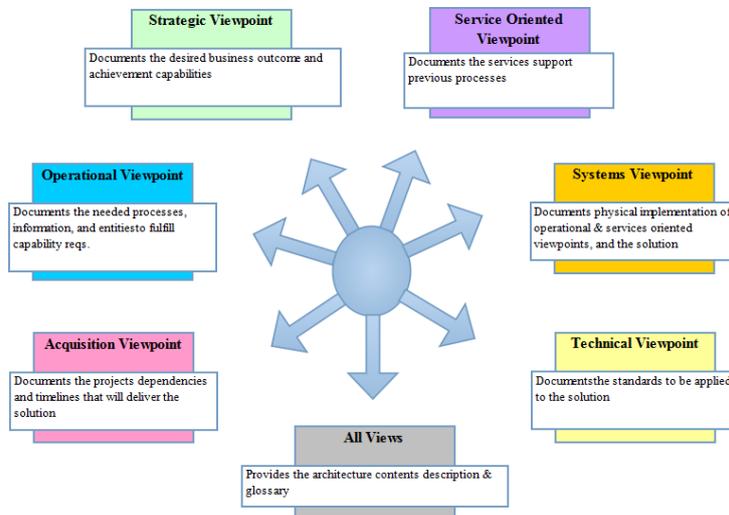


Fig. 6. MODAF seven viewpoints for ICDI firm

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 12, December 2013

2) *Defining Requirements:* To describe these tools clearly, they are applied to a real system that is an industrial firm is considered as a second tier to vehicles assembly firms and this is one of the company's varied activities. This plant is needed to fulfill customer requirements, so it has its entire requirements and validation system to ensure its ability to compete and test solutions of improvement. Teamwork is configured to discover the considered requirements, Viewpoint Analysis (VPA) is a tool of requirements gathering and data analysis tools, which has been applied to identify requirements, as illustrated by Figure 7. The main boxes present the functional requirements, while the surrounded ones are non-functional requirements (constraints).

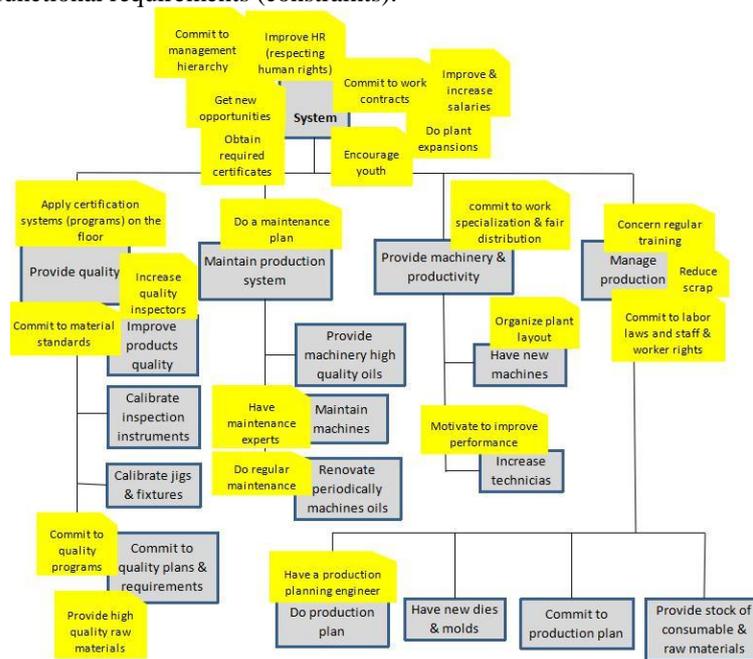


Fig. 7. VPA - the final viewpoint structure chart for ICDI firm

3) *Optimizing Proposed Alternatives:* The teamwork is considered to explore and assess the proposed alternative solutions not to be a temporary solution for present but to be comprehensive for all levels, so Need Means Analysis (NMA) - the box of nine - is a proper alternatives investigating tool for this issue, as illustrated by Figure 8. This example presents treatment and painting department issues that result in non-qualified painted parts of treating and painting processes. The central box contains the current SOI; the treatment basins and painting unit. Its operational requirement (OR) is to treat and paint finished parts. There are three system levels the higher level considering new systems thinking, the same system level is to improve the current SOI with a new architecture, and the lower level treats new subsystems.

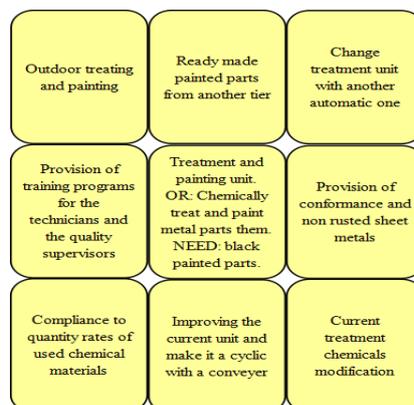


Fig. 8. Need Means Analysis for ICDI firm treatment and painting unit

4) *SOI Modeling*: To present the system and state the issues for any system of interest, firstly the actual system process life-cycle has to be understood and then identifying points of weakness through this life-cycle by modeling the system life-cycle using V-model as a system development tool as illustrated by Figure 9. This model presents the firm processes life-cycle starting at defining customer needs until delivering orders, it is obviously noticed that the main points of lack lie on:

- Receiving of raw and consumable materials,
- Products quality,
- Order delivery time (delay time), and
- Management (organizing orders and communications between administrations).

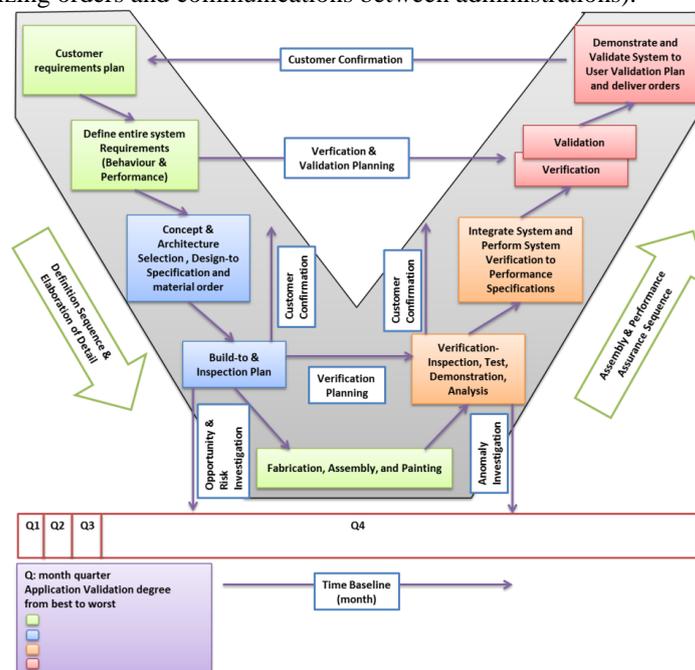


Fig. 9. V - model of system engineering processes for ICDI firm

5) *System Verification and Failure Analysis*: It is required for any system to verify and assess its performance, cost, and risk to ensure it is on track for fulfilling customer needs, also to verify and continuously assess system performance that is useful for feedback and re-evaluating the system. Quality Function Deployment (QFD) is a tool for detecting system development and relationships among main functions, as illustrated by Figure 10. The QFD, - as known - its left side presents the voice of the customer, the roof presents the voice of the company itself, and the lower part presents how the company shall fulfill customer requirements. The parts of comparing the current company to other customer's tiers and to measure the company gap to targets its weight is calculated by; $[\sum (Priority \times Relationship)]$, where the priority is the customer importance and the relationships presents the value assessment matrix between the voice of the customer and the voice of the company.

6) *System Integration*: Integration means designing interfaces and bringing system elements together so they work as a whole. This requires extensive communication and coordination. Interfaces between different subsystems, the main system and the customers must be designed. Subsystems should be defined to minimize the amount of information to be exchanged between the subsystems. Figure 11 illustrates the use of an interfaces tools that is N^2 chart. This N^2 diagram represents and analyses the functional or physical interfaces between system elements. As shown by Figure 10, the central main blocks presents functions (system elements) numbered by $F(n)$ according to the function number, the upper side of this matrix presents the forward relationship from function to another, and the lower side of the matrix presents the backward relationship.

Proposed SELTMF Model Application Validation

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 12, December 2013

During the operating of the SELTMF on the system life cycle the performance of the system should be developed. Initially the following measurements will be done to validate that the system is in compliance with its requirements. The system is assessed by using some performance measures, some enterprise Key Performance Indicators - KPIs for the whole investment [24], are used to assess the system and compare the situation before applying the SELTMF and during applying it. These measures are applied to the application firm during two periods one before applying the SELTMF and the other one is during the application of this proposed model as an assessment method. Each period is three months means a quarter of the year (Qrt). The suggested KPIs are illustrated by; Table 1 that represents the needed measures for these KPIs, and detailed analysis of these KPIs and how to be calculated are illustrated by Table 2.

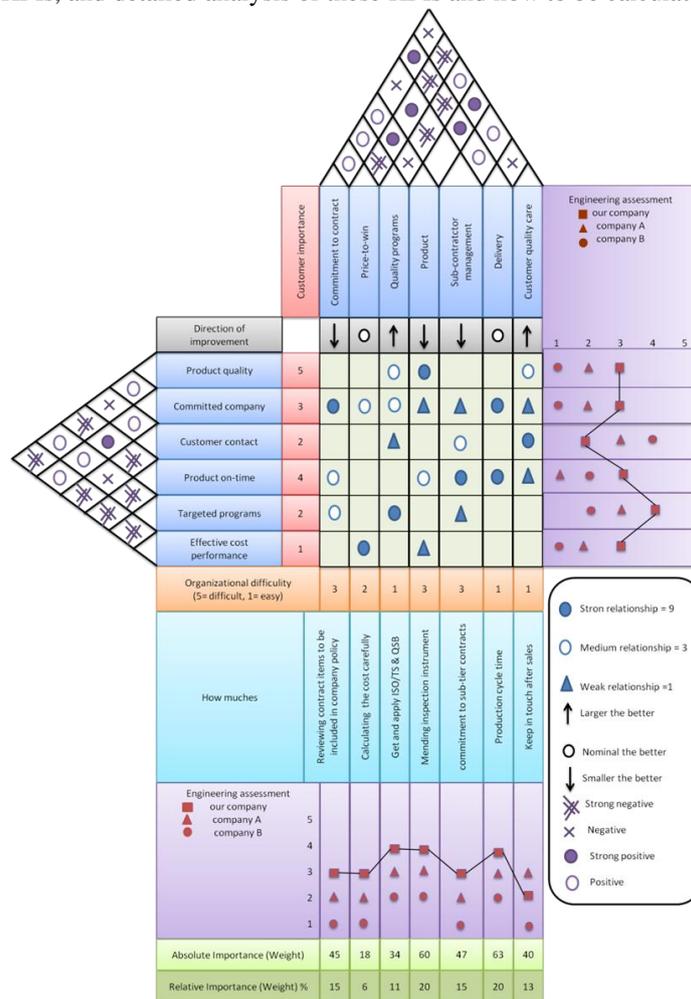


Fig. 10. An example of a system overall Quality Function Deployment for ICDI firm

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 12, December 2013

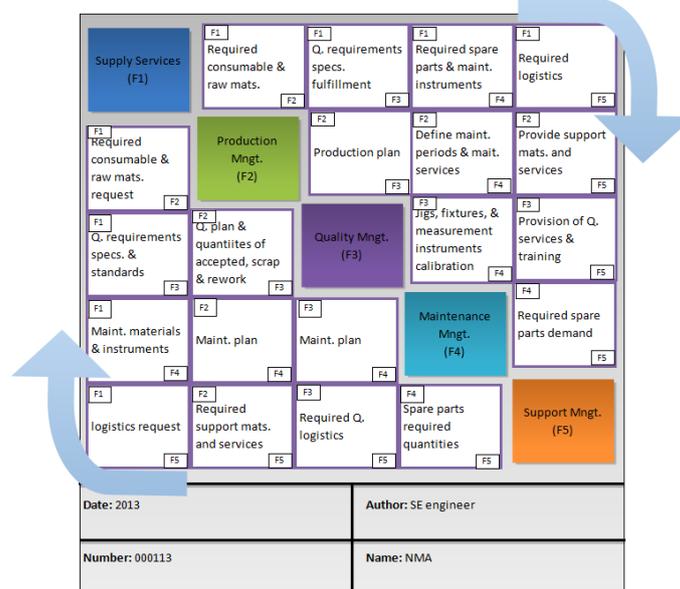


Fig. 11. N² chart for ICDI firm

Table 1. Needed measures data for the KPIs from ICDI firm through two quarters

Measure needed to calculate the KPI	Value	
	Qrt. 1 (Previous state)	Qrt. 2 (Implemented SELTMF)
Total (T.) Firm Revenue (Output) (L.E)	1,500,000	3,000,000
T. Firm Costs (Input) (L.E)	968,970	1,394,355
T. Labor Costs (L.E)	179,904	217,950
Material cost (L.E)	540,000	900,000
Raw material Inventory money value (L.E)	180,000	300,000
Total number (T. #) of products (unit)	159	183
T. Over time (L.E)	145.46	145.46
Number (No.) of labors	101	101
Ordered material time (day)	20 (-10)	10
Deliver time of products to customers (day)	29	20
No. of M/Cs (unit)	54	54
Working time (hr)	544	736
Available time (hr)	496	688
$\sum M / C_s$ down time (day)	2.72	2.72
T. quantity of used material (ton)	150	150
No. of defective products (unit)	12,871	3,497
T. # of produced products (unit)	588,078	783,024
No. of reworked products	33,870	671
No. of new customers	0	3
No. of customers	17	20
No. of orders delivered on time	0	7
T. # of orders	9	9
No. of solved claims	0	3
T. # of claims	3	3
Order delivered time (day)	20	20
Order received time (day)	30	22
No. of trained employees	0	15

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 12, December 2013

Measure needed to calculate the KPI	Value	
	Qrt. 1 (Previous state)	Qrt. 2 (Implemented SELTMF)
T. # of employees	137	137
T. training hours (hr)	0	24
No. of new products	0	2
No. of good quality (sound) units produced	541,337	778,856
Processing cost / unit	0.423	0.353
Rework cost / unit	(1.77)	(1.77)

Table 2. Detailed KPIs and calculation methods

Perspective	KPI	Method of calculation [24]	Period (Qrt=3 months)	
			Qrt. 1	Qrt. 2
Financial	Total Productivity of Firm (TPF)	Total Output / Total Input	1.548	2.152
	Partial Productivity of Labors	Total Output / Total labor cost	8.338	13.765
	Partial Productivity of materials	Total Output / Total mat. cost	2.778	3.333
	Profit	Total revenue – Total cost	531,030	1,605,645
	Inventory Level (Raw material)	Value of money of the raw material inventory	180,000	300,000
Internal Business	Unit Cost	Total cost / Total No. of products	6,094.151	7,619.426
	Over Time	Total over time / No. of labors	1.440	1.440
	Overall Cycle Time (days)	Ordered mat. time – Deliver time of product to customers	39	10
	M/C Utilization	(No. of M/Cs x Working time) / (No. of M/Cs x Available time)	1.097	1.070
	M/Cs Down Time %	(Summation of M/Cs DT) / (No. of M/Cs x Available time)	0.081	0.058
Quality	% of Defective products	No. of defective products / No. of produced products	2.189	0.447
	Rework %	No. of reworked products / T. # of products	5.759	0.086
	New Customer %	No. of new customers / No. of customers	0	15
	On-Time Delivered Order %	No. of ordered delivered on time / T. # of orders	0	77.778
	Solved Claims (Customer Complaints) %	No. of solved claims / T. # of claims	0	100
	Average Lead Time	Sum of (Ordered delivered time – Order received time) / Total # of orders	1.111	0.222
Innovation & Learning	Trained Employees %	No. of trained employees / T. # of employees	0	10.949
	Total training hours per employee	T. training hours / T. # of employees	0	0.175
	No. of new products	No. of new products	0	2
Integrated Measures	Quality – Productivity Index	No. of good quality units produced / ([T. # of units produced x Processing cost per unit] + [No. of defective units produced x Rework cost per unit])	1.994	2.756

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 12, December 2013

Perspective	KPI	Method of calculation [24]	Period (Qrt=3 months)	
			Qrt. 1	Qrt. 2
			Value Added	Revenue – Mat. Cost
Value Added %	Value Added / Mat. Cost	177.778	233.333	

The analysis of the company performance ensures that due to SE application the company started to improve its performance as illustrated by measures. This is noticed through: a significant increase of the firm total and (labors, materials) partial productivity, quality-productivity index, profit, and value added almost by (28%, 39%, 17%, 28%, 67%, and 54%) respectively, noticeable positive decrease of defective products percentage, rework, and lead time almost by (+100%, +100%, and +100%) respectively, also acquiring new customers and new products, besides developing training programs, and solving customer claims.

CONCLUSION

While there are challenges implementing any approach, it is possible to get some helpful information and recommended reforms. Many organizations divide their Systems into three main categories according to their major workflows that is recommended to be done into this company of application: Requirements definition, Architectural design and Testing and verification. This firm as like many companies its priorities are based on cost and revenue, that is not a flaw but it does not realize that in order to get high marks for low cost it should be interested in three major pillars: Human factor, Administration hierarchy organizing, and Quality issues. This enterprise system should set up a configuration (modification) management and project management All of these SE activities must be documented in a common repository, it could be hardware or software.

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