Constructability: The Prime Target in Value Engineering for Design Optimization

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Abstract –

An ideal Design-Construction Interface is assumed in the decision making process of initiation and planning. The uniqueness, site conditions and contingencies cannot be envisaged and incorporated in its entirety in all projects. Constructability in resonance to the appropriate technology becomes paramount in deciding the material, structural forms and construction methodology. The construction industry is gradually evolving to a manufacturing and product delivery process where design for Manufacturability and Assembly takes precedence. Optimization of targeted values viz logistics, manufacturability, assembly, maintenance, lifecycle cost and ergonomics becomes critical to ensure smooth execution of the Project. The data collected from a pre cast construction project is analysed to map the degree of ease in Design-Construction interface and compared with a framed structure to draw parallels with respect to constructability as a target in value engineering. The objective of the study is to examine the components of constructability in Design Process to optimize effort and resources. Target Value Design gives the stakeholders more rationale inputs for monitoring and decision making. The study attempts to predict the future of manufacturability and constructability in construction where smooth assembly with minimum labour is essential for value addition. The bottom up approach of new policy initiatives and better communication between stakeholders promise more refined designs in future where technology will be pushed to achieve design optimization.

Keywords –

Constructability; Design Optimization; Value Engineering; Design-Build; Target Value Design; Manufacturability; Assembly

1 Introduction

It is an intriguing task for designers across the globe to take a foolproof final print of the drawings and precedence diagrams incorporating all possible changes during execution of a Project. Unfortunately we do not have the ability to speculate and predict the future. But we do have the ability to learn from the past and adopt better practices in the next project. An ideal condition is assumed by the planners while formulating the conceptual design. Building construction industry suffers greatly from cost and time overrun due to oversights in planning and design inaccuracies. The success of a project is decided by the Value it provides to the user. To provide 'Value' to the client, the concept and its execution has to be well coordinated to provide the best performance. The term Design encompasses all activities in the design studio including concept, schematic, design development, preparation of tender documents and entering into a legally valid contract for construction. According to Jergeas et al. [1] and Cleland [2], efficient management of the relationship between the project and its stakeholders is an important key to project success. Conceiving the plan in a broader framework and executing it with minutest detail with optimization of all resources is possible only when the details are constructible. For this to happen, communication between stakeholders is must. In their study of critical success factors across the project's life cycle, Pinto and Slevin [3] emphasize the importance of interaction with the clients throughout the duration of the project. Almost 40% of the change orders or deviation orders are rooted in the design phase [4] and 30% cost escalation is attributed to poor communication during design phase [5]. This amply highlights the importance of reducing the change orders during execution phase and targeting constructability from the planning stage. Constructability translates to be the ability to construct something with appropriate technology within a specified budget and schedule producing intended value. Value Engineering has to be an integral part of constructability as its prime aim is to increase value than to reduce cost [6]. The design table is very much a place where the fate of the project lies and decides the value it will generate. The constructability and value generation is critically analysed in adopting an emerging technology like pre cast construction to draw lessons in design optimization along with procurement management challenges.

2 Constructability and Value

Right from the very first house human beings constructed, the intended purpose was his concern. 50,000years ago the concern was only to provide shelter from weather and safety from wild animals. The need to design a product was felt when he realized that the final outcome was not matching the imagined one. As we evolved the scope got expanded towards gaining more utility from the same effort. The difficulties faced during execution were traced back to the plan and it was realized that the lessons learned should be incorporated in the next design. Target Value Design gives the stakeholders more rationale inputs for monitoring and decision making. Target Values have to be identified to incorporate in the design process which might vary for each stakeholder. The study aim to define values in a design process for optimization of resources. Forensic Schedule Analysis of a pre-cast housing project is carried out to study the Design-Construction interface fault lines which cause hiccups in achieving intended values. The study examines the various constructability factors influencing the smooth interface from design to construction and critically examine the bottlenecks. For this purpose the concept of Value needs to be addressed in a more objective way.

2.1 Value in Design

Value is a set of concerns with respect to cost and function. It has a futuristic component which is based on a various inputs and assumptions. It can be expressed as ratio of design function to cost. It is quite obvious that in order to increase value, the cost has to be reduced or the design functions have to be increased. But while preparing a tender document, in the process of procurement, the price is the only readily available factor. A correlation between price, cost and value need to be established to define the target values in design. Table 1 illustrates the comparison of price, cost and value with respect to various functions as obtained from focus group discussions with stakeholders in construction projects. It can be seen that value is a user's utility perspective through opinion. This opinion could be based on a single factor or a combination of factors. The comparison illustrates that price is related to past tense, cost to present tense and value in future tense when we evaluate a facility or a project at planning. The price comes from the market and documented in the schedule of prices by various agencies and the cost is budget at completion of the project. The value is an opinion which goes back to market as set of benchmarks with respect to utility of the product or service. Figure 1 gives the flow chart of value generation in a typical construction project.

Table 1. Comparison of Price, Cost and Value

Price	Cost	Value
Amount paid for acquisition	Amount incurred in production	Utility of a product or service
Ascertained from consumers perspective	From producers perspective	From users perspective
Estimates through policy	Through fact	Through opinion

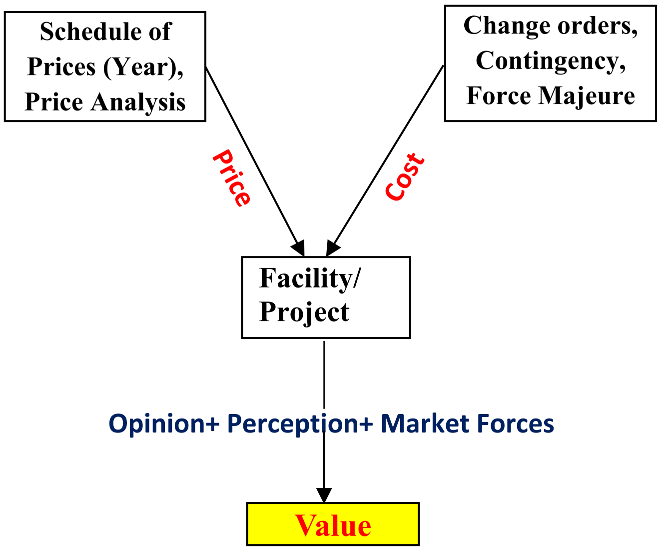

Figure 1. Interaction of Price, Cost and Value

Price is a fixed factor compared to cost and value. It is obtained from schedule of prices which is periodically updated by regulatory bodies. In a Project it makes sense to plan cost cutting, but not price reduction. Price of materials are fixed with respect to time and location. These are 'fait accompli' and we can only opt for the most suitable in terms of economy, quality and availability. Cost is what the client pays to own a facility [7]. Once the BOQ is prepared the price factor has been considered. But the cost factor eludes the designer as that is depended on change orders, contingency and force majeure. Value is a promise in future which is based on opinion, perception and market forces. In order to optimize the value what should we aim for? The answer probably lies in the way we produce an automobile or an aircraft. Though a civil engineering project cannot be templated into a product manufacturing process, many lessons can be drawn from the evolution of assembly line manufacturing process which revolutionized the industrial production of construction materials.

2.2 Constructability in QFD

Quality Function Deployment in construction industry is not often practiced due to its invisibility compared to other manufactured products. A direct translation of QFD concept from an automobile production unit may not suit a building contractor. Customer's aspirations from a car varies greatly from a building or an apartment. Constructability is the synthesized end product after analyzing all QFD inputs. Table 2 illustrates the conflicting yet complementing requirements of users and designers while planning a pre-cast apartment building. Customers are often smitten by the cost not by the value. At the same time cost eludes the designers as they are indulged in price. These conflicting demands in constructability makes it more challenging to set specific targets for planning the project.

Table 2. QFD requirements of Customers and Designers for a Pre-Cast facility

Customer	Designer
Should be Earth Quake proof	Monolithicity of connections
Smooth finish	Vibro Compaction
Low maintenance cost	Easy access to MEP lines
No disputes	EPC Contract
Affordability	Break even quantity
Fast delivery	Steam curing of RCC members
Quick assembly	Cranes part of inventory

2.3 Genesis of Pre-Cast Technology

The pre-cast construction technology was emerged as a natural evolutionary process by improving on the lacunas of cast-in-situ construction. The advancements in reinforced concrete technology and feasibility of slender sections made designers to take a bold step towards treating the concrete members like steel. From the table 1, it is very evident that the industry has adopted pre-cast technology for achieving value by taking advantage of certain unique features of the new technology.

Table 3. Comparison of Pre-Cast vs. Cast-in-Situ

Pre-Cast	Cast-in-Situ
Cast and cured in manufacturing plant	Members are cast at construction site
Accelerated curing required	Normal curing time
Faster Construction	Slow Construction
Greater control on quality	Less control on Quality
Not hampered by adverse weather	Severely hampered by weather
Assembly based	Activity based
Minimum waste	Considerable Waste

From construction activity, the entire process got converted to a manufacturing process to add value. In an evolutionary curve we can see that steel overtook cement concrete as a preferred material for fast track construction. Though the shift towards steel for many high rise buildings in mid-20th century happened intuitively, a closer look will show that it was a natural option for the rapid rebuild of post war Europe. True to the old adage, necessity was the mother of invention and a solution emerged with less labour, time and superior finish. It is interesting to note that though the technology is not based on any new theory, the adoption happened by default, not by design. The reason is more value generation through manufacturing and assembly. Pre cast system is widely used now in many repetitive structures and claddings due to its versatility to act both as architectural and structural material.

2.4 Cost Benefit Analysis and Break Even Quantity

The actual value of pre-cast is often misunderstood as the direct cost of structural components will be high compared to the cast-in-situ framed system [8]. The components have to be manufactured in a pre-cast plant and transported to the site. Huge initial investment of casting plant and steam curing facility can be justified only with a minimum assured order of repetitive nature. This technology is ideally suited for housing sector as the layout is similar and slabs are spanning less than 5m. The Cost Benefit Analysis in figure 2 shows that minimum number of 800 units have to be constructed to make the rate comparable to the conventional cast-in-situ technology.

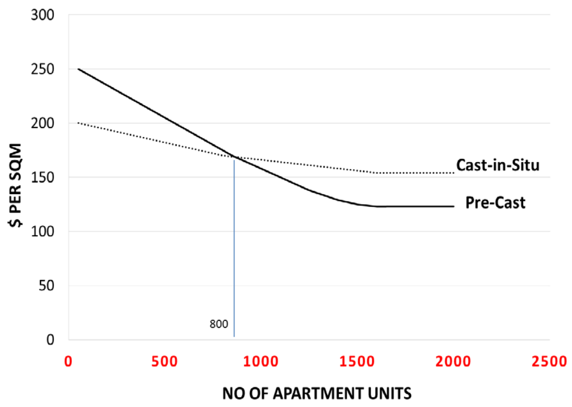

Figure 2. Break Even Quantity for Pre-Cast feasibility

This break even quantity is specific to a turnaround distance as the distance of plant increases from the construction site, the cost changes. Figure 2 shows the data collected from Delhi, India. The construction firm which invested almost $7 million on the plant definitely had a look at the national policy on the housing sector which pledged 1.5 % of GDP towards the cause.

3 The Design Targets

Having defined the relation between Price, Cost and Value; it's time to fix the design targets specific to the intended value. They could be Assembly, Modularity, Manufacturability, Maintainability or Logistics (AND/OR). These target values may be required in varied quantities as per the design optimization which should fit in the cost and time framework. The present study is focusing on Precast Technology and obviously the targets have to be assembly, manufacturability and logistics.

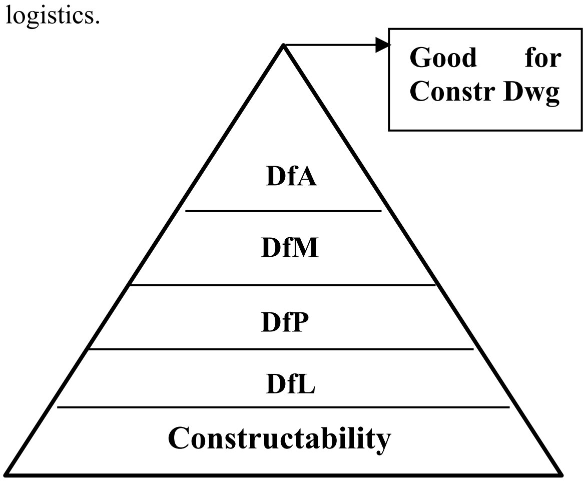

Figure 3. Target Value Triangle

A close examination will show that the relative importance of Assembly and Manufacturability is more predominant than logistics or transportability. Location of a manufacturing plant can be selected as per the logistical requirement but if the components are not fit for assembly, there is no scope to perform any repair on site. Taking them back to the plant for changes will incur huge financial burden which may derail the whole financial plan. The target value triangle for the pre cast construction project is shown in figure 3. As time progresses, the influence of design aspects of logistics starts reducing and manufacturability increases. The iterative design process zoom in on to design for Assembly as the prime target to achieve in the design process and constructability remains the superset of Logistics, Manufacturability and Assembly.

3.1 Design for Logistics (DfL)

The Pre-Cast components have to be manufactured in a location which makes the turnaround time logistically feasible and economically viable. The location of the plant has to be decided based on the availability of the raw material and resources. The logistical challenges involves setting up the Pre-Cast plant, Transportation of raw materials and Transportation of manufactured components to the construction site. The dimension of vehicles for the above purpose will be governed by the size of the building components and their weight. The maximum height clearance permissible under the rail bridges and fly overs on the way plays an important role in this logistical planning. Once the location of manufacturing plant is fixed, rest of the parameters will be dependent on this aspect of logistical baseline. Figure 4 shows the map of three sites A, B, C and the location of the pre-cast plant, P. The location of plant is so selected that the time to reach each site is almost same. The plant is sited based on the logistical feasibility which has a direct bearing on the overall cost and thereby being a value deciding factor.

3.2 Design for Manufacturability (DfM)

The components have to be pre cast in the plant and assembled at the site. This assembly operation will be requiring cranes. That infers to the correct size and shape of components which will make the assembly easy. Assembly will govern manufacturability. The beams, columns, floors and walls have to be cast in the casting yard. The dimensions of structural components have to be fixed and ready mix concrete is poured using automated systems. How can compaction be achieved? A normal vibrator cannot be used as it will consume more time and will result in non-uniform compaction. The casting bed has to act as a vibrator to save time and effort. This important criteria for casting bed design and the cost involved is a governing factor in manufacturability. The components have to be cured for required period to attain full strength and this for fasten the process, a steam curing facility has to be set up. All members should be hoistable using cranes as they will be moved several times once removed from casting bed. The location of these lifting hooks will have to be decided on the drawing table as they are part of structural analysis process. Table 4 lists the criterion considered for manufacturability of pre-cast technology.

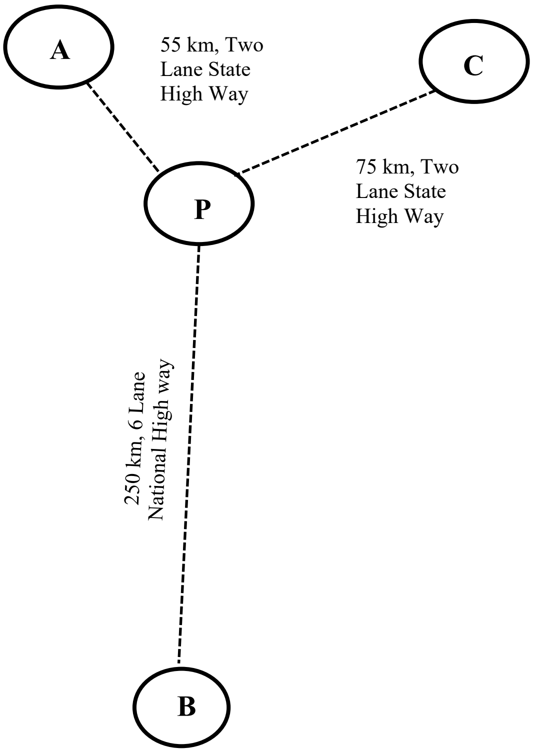

Figure 4. The Location of Plant P, with respect to sites A,B and C

Table 4. The Manufacturability criterion

Criterion	Manufacturability
Concreting	Automated Concrete Pouring Facility
Compaction	Vibro Compaction of Casting Bed
Curing	Steam Curing Facility
Mobility of Components	Overhead Crane in the Plant
Execution at Site	Limiting the weight of each components to the crane capacity at site

3.3 Design for Assembly (DfA)

Assembly of various structural components at site has to be in perfect sequence to ensure a smooth execution. Unlike the cast-in-situ method, the pre-cast members lack monolithic connection. The structural analysis is carried out based on certain rigidity of connection and these design assumptions have to match with the site conditions. In reality, the DfA is the most important factor in a pre-cast design process. If the connections are not strong enough, catastrophic failures might happen. After the structural analysis and design, a scaled model may be tested in lab condition to ensure that the assumptions are correct. The cost for these tests has to be borne part of the Research and Development effort rather than in the estimates of the design at hand. These are part of the initial investments as it is practically impossible to carry a destructive shake table test every time. The results of the initial test can be interpolated or extrapolated in subsequent designs as the case may be.

After taking into account of logistics and manufacturability, the ease of assembly takes precedence. The aspect of assembly is so important that the structural design has to be carried out by taking these assembly into consideration. The design of floor slabs will illustrate this aspect in detail. Unlike a cast-in-situ slab, the pre cast slab has many functions to perform. It should have shear connectors to ensure connection between next slabs, it has to give a smooth floor finish and it should be easily liftable by crane. These functions are possible only when the design is robust, flexible and innovative. A lattice girder reinforcement is specifically manufactured for the purpose and this girder serves many purpose. Figure 5 shows the manufacturing process and figure 6 [9] shows slabs stacked after curing process which are ready to be transported to the site.

Figure 5. Lattice Girder Manufacturing (Courtesy: BG Shirke Group of Companies)

Figure 6. Shear key as Lifting Hook in Lattice Girder

4 Monitoring and Control

The traditional monitoring and control process is designed to keep the budget always on track and effect minimum change orders. The stakeholders involved are reacting to the precedence diagram actual unravelling on site. In pre-cast system, the construction activity has been converted to an assembly process. So the monitoring process almost reduces to an assembly supervision as there are very few decisions to be taken during construction. The scope is fixed in pre-cast the moment construction drawings are issued to the casting plant and no change order with respect to architectural or structural is feasible. This lack of flexibility is accounted for by numerous design iterations after repeated interactions with stakeholders.

5 Procurement Management

PMBOK has covered forty nine processes in ten knowledge areas and five process groups in its 6th edition [10]. The processes involved in procurement management is limited to plan, conduct and control. In conventional construction management, the procurement is a reaction to what is designed. But when we plan to adopt an assembly based technology, the procurement management cannot be independent of the design process. The Design-Build format suits procuring the pre-cast systems as the bid preparation is challenging when it comes to design and estimation. In an open competition to bid for a specific design, the purpose of providing equal opportunity and level playing field is not achieved. Moreover the DfA challenges will make the design favour a particular firm who has adopted a specific dimension for their projects in hand. Using design-build procurement format, the owner saves time and effort by executing only one contract with a design–builder, who takes responsibility for completing both the design and construction of the project [11]. The Engineer, procure and Construct (EPC) model is often considered synonymous with Design-Build one in function as both shift the design and build responsibility and a bigger portion of risk to the contractor [12]. In EPC mode the contractor is often entrusted with the desired output in the case of a production facility. In a construction project like precast mass housing, design-build provides more value. The evolution of any technology has taken considerable settling time before the rest of the world catches up with a universally accepted price for procurement. A market survey will show that construction firms which innovated to adopt faster and durable construction technology are faring better than those who continued with older ones. From clients perspective, (s)he may opt for any technology or procurement format which gives a better return. In the Design-Build system, the designer, the builder and the consultant, all could be rolled into one due to uniqueness of technology and there may be very less control by the client over the Project once the design has been finalized. But the designer has to ensure assembly, manufacturability and logistical feasibility by taking the client on board. Keeping the architectural, structural and MEP changes out of purview, the Work Breakdown Structure and the activity precedence diagram can now be fixed. This facilitates the designer to provide exact quantities for the QS team which makes their task of estimation much effortless and almost accurate.

5.1 Design for Procurement (DfP)

Design for Procurement (DfP) is also an important parameter in construction when it comes to innovative and emerging technologies. Every exotic design cannot be constructed and every technological feasibilities are not buildable on ground. There is a fine line between building a design and design something buildable. In the former case, the procurement team is searching for solutions which were not considered by the design team. In the latter, design office is involved in the procurement decisions. In the pre cast example, the activities are designed to be repetitive so that once the components are manufactured, transporting and assembling completes the construction process. The design is tailor made for procurement to suit a Design-Build system so that the facility is built by the firm which designs it, thereby eliminating communication hiccups between a consultant and contractor. But is this killing fair competition and leading to monopoly of business? This question lingers on with all new innovations where very few people are experts initially. Any technology can compete for design parameters like minimum waste generation, faster construction and minimum cost per unit plinth area. The fittest and adaptable will survive and probably the theory of evolution is applicable to construction industry too.

6 Modularity: The Modern Solution for Constructability

Modularity has emerged as a modern day solution to ease the construction complexity. The design complexity of assembly can be smartly eliminated in the modular approach. Similar to the pre cast technology, on a larger scale modularity reduces the project cost [13]. The concept of modularity was borrowed from the shipping transportation containers which offered quick loading and unloading of cargo from ships. The uniformity of the containers and cranes made the cargo handling very smooth saving billions of dollars in demurrage. This path breaking idea can be simulated in construction too where the rooms are relatively small in dimension. The design for modularity assumes complexity as the height of the building increases due to higher seismic design requirements. Unlike a pre cast building, a modular building is 100% reusable and relocatable having few beam-column-slab connections. In modular system, rather than member strength, the geometry is holding the structure together.

7 Constructability in Design Optimization

It is quite evident that constructability is a function of many parameters like assembly, manufacturability, logistics, procurement, cost and time. In order to take the best out of technology, we have to move away from the traditional network crashing mindset to dynamic parameters mentioned above. The time saving techniques employed by the defense forces may not fit for a building project. The forces may not be worried about the budget but in construction projects, the client is worried about the cost. It is imperative that constructability has to be considered as the benchmark for value generation. The figure 7 depicts the relative importance of various design targets to mix and match the optimum one. The most suitable targets can be given more weightage and design optimized according to the technology involved.

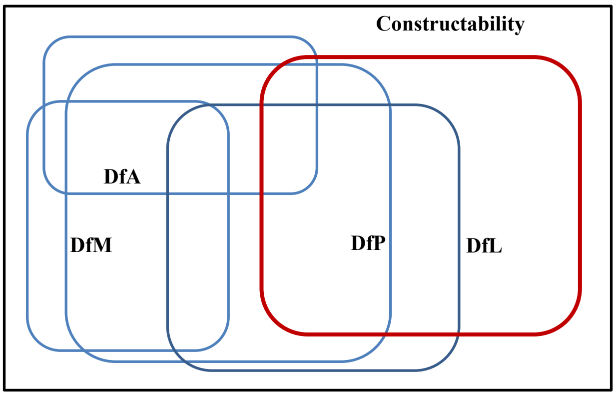

Figure 7. Design Targets in Constructability

Constructability is pitched as the superset in which various other design target sub sets are accommodated as per the requirement. It is more of a tailor made solution rather than pre fixed one. The study reveals the relevance and influence of procurement management on constructability and importance of value generation in construction industry.

8 Stakeholder Synergy and Design Optimization

Better communication between stakeholders is a pre requisite for optimizing the effort and resources. This can be achieved by clash detection at an early stage. Design is a cocktail of disciplines and technologies which often lack the similar wavelength of people and ideas. The diverse opinions and assumptions need to fit in to the design parameters suitable for the project in hand. Communication between stakeholders is highly influenced by the structural system and procurement methodology. The constructability components like DfA, DfL, DfM and DfP is examined for a specific technology ie Pre-Cast. Similar analysis of design targets might have to be carried out for other construction methodologies too. It is pertinent to mention that in the example of Pre-Cast the procurement mode was Design-Build as the builder was responsible for the architectural, structural and MEP design. Better stakeholder synergy is achieved in this case as one stakeholder viz consultant has been eliminated. Previous studies have established that 40% of the change orders are rooted in the design phase and 30% cost escalation is attributed to poor communication during design. At the same time it has to be noted that each facility is unique and a tailor-made approach have to be adopted for different scenarios. The design team has to work out the best cocktail of design targets to achieve maximum value for the project not compromising on stakeholder synergy.

9 Conclusion

The human race has travelled a long journey from Pyramids to Burj Khalifa. As the theory of evolution has proved, only the ergonomic design will be passed on and imbibed by the next generation. Economic viability with desired value will remain the sole criteria for the project's success in the modern world. Only constructible designs will be executed and a trade-off will be arrived between design and construction which could be an iterative process to reach at minimum financial burden, carbon foot print and maximum value for money. The monitoring and control techniques like EVM will be helpful only when Design-Construction interface is hitch free. Construction is a nation building exercise where each activity is contributing towards the GDP. The study validates ample reasons to predict a symbiotic relation between various procurement options and technologies to achieve targeted values. Design and Construction will remain complimentary activities with the constructability deciding the success and client satisfaction. The study predicts that constructability coupled with smooth assembly using minimum labour is essential for value addition. The bottom up approach of new policy initiatives and better communication between stakeholders promise more refined designs in future where technology will be pushed to achieve design optimization.

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