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A. FOŠKULO *

KONČAR – POWER PLANT AND ELECTRIC TRACTION ENGINEERING INC.
CROATIA

M. KOKORUŠ

ENTEGRA EYRICH + APPEL GMBH
GERMANY

Streamlining the Decision-Making Process on Tubular Rigid Busbar Selection During the Planning / Designing Stage by Utilizing 3D Substation BIM Design Software

SUMMARY

For Utilities, each substation is regarded as an asset. Managing of assets is one of domains of Asset Management including Life Cycle Costing (LCC) as a decision-making criterion. However, LCC as a decision-making criterion should be applied on an entire substation taking into account all of the potential cost influences for the purpose of achieving of an effective substation management. Asset management as a decision-making process should be observed within a larger context and should be more focused on risk management, as all real decisions include an element of risk due to present uncertainties.

Two promising avenues are explored in regards to more comprehensive and rigorous up-front planning through usage of Information Technology (IT). While up-front planning falls under the domain of Lean philosophy, Building Information Modeling (BIM) falls under the category of agile decision-support tools. Utilization of both is explored from a perspective of design-uncertainties under both product and process design.

Standard specifications and standard designs are another form of applied Lean Philosophy that reduces design-uncertainty and variability. However, a range of technical solutions stemming out of the standardization can be quite wide. Customization involves specification and design of new / innovative designs with wide range of technical solutions as well. Due to external pressures focused on shortening of the project delivery time, there is a need for a faster project time throughput. This is reflected in the form of a requirement for more rapid engineering decision-making and faster decision cycles.

Streamlining of a decision-making process related to the engineering is all about engineers' awareness of the situation from the project level perspective coupled with utilization of decision-support tools for creation and reuse of knowledge. Plan – Do – Study – Orient (PDSO) cycle is a decision-making model that supports creation and reusability of knowledge along with providing an explanation in regards to the time dimension relating to decision-making, and as such is presented in this paper.

The rigid busbar system design is an iterative process influenced by many factors, defined either as design variables or design constraints. As rigid busbars are gaining more popularity for both greenfield and brownfield investments, the rigid busbar system design is explored from a perspective of decision-making streamlining. The case of the rigid busbar system design of El Chaparral project in El Salvador is given.

KEYWORDS

Lifecycle – Decision – Design – Standardization – Customization – Lean - Agility – Calculation – BIM - Busbar

INTRODUCTION

As forecasted in [1], the demand for electricity is expected to increase by more than two-thirds between 2011 and 2035. Utilities are already under pressure to extend the useful life of aging assets beyond their original expected life time [2]. As reported by [2], improvements regarding cost, time and quality during the project delivery are required, thus leaving space for improvements for making right decisions and to deliver projects more efficiently across an array of asset types.

For Utilities, each substation is regarded as an asset. Managing of assets is a domain of Asset Management with Life Cycle Costing (LCC) as a decision-making criterion [3]. Doing so, the main goal is to minimize the total cost of a substation [4]. However, LCC as a decision-making criterion should be applied on an entire substation taking into account all of the potential cost influences, as opposed to its often application on substations individual components, with the purpose to achieve an effective substation management [5]. These additional cost influences are related to land costs [5] [6], but also to costs for the balance of the plant as well, representing steel structures, concrete elements, transport and installation, among all others [6]. Engineering should also be included as a cost into the system and equipment cost [6]. The same relates to renewal costs [7]. The following figure represents a LCC basic structure for high voltage (HV) substations.

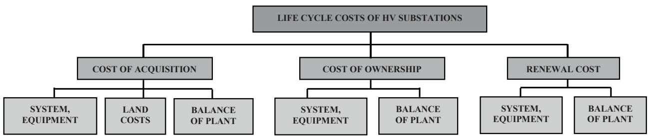

Figure 1. Prime levels of the basic structure of the LCC assessment for HV substations [6]

Asset management, in general, as a decision-making process should be observed within a larger context and should be more focused on risk management [8]. According to [9], risk management is defined as "*a decision-making to balance risk and risk mitigation*".

All real decisions include an element of risk as all decisions are usually made under uncertainty [10]. Uncertainty in engineering can be classified either as content-uncertainty (incompleteness, imprecision and vagueness) or as context-uncertainty (unreliability, invalidity and instability) in regards to information quality [11]. In order to make rational decisions, information needs to be full, current and reliable [12]. Apart from advising improvements in decision making, improvement of the information flow is also advised. An effective information flow represents a basis for an effective decision-making [13]. Two defined promising avenues are, according to [14], the introduction of more comprehensive and rigorous up-front planning, and enhancement of Information Technology (IT) capabilities.

Section 2 of this paper represents a literature review section in which following topic are covered:

- Design-uncertainties from a process design perspective;
- Design-uncertainties from a product design perspective;
- Pursuing optimization through utilization of decision-support tools;
- Decision-making models from the lens of agility, and;
- Rigid busbar design process, variables and constraints.

Inside section 3, a recapitulation of the literature review section is presented before defining research questions as a part of the problem statement. Section 4 relates to the presentation of up-front Building Information Modeling (BIM) utilization as a solution of a problem. A busbar system design example from the recent project El Chaparral in El Salvador is given and described inside Section 5 of this paper, before setting forth a discussion relating to the busbar design example from a perspective of utilization of up-front BIM engineering inside Section 6. A conclusion is presented inside Section 7 relating to streamlining of decision-making process for the rigid busbar system design. Such a conclusion can be generalized and applied to other parts of power substations as well. Last sections of this paper are related to the presentation of recommendations and acknowledgements before outlining references.

LITERATURE REVIEW

DESIGN UNCERTAINTIES FROM PROCESS PERSPECTIVE

As decision-making is an integral part of any design process [9], uncertainty in the design process is referred to as design-uncertainty [15], which will, if not addressed, ultimately lead to engineering reworks and project delays [16]. According to [17], a general view is that uncertainty is the highest at the beginning and then it is reducing during time with generation of relevant information that is made available. Resolving of uncertainties early in the project is highly advised [16]. In general, dealing with uncertainties is labeled as "Lean" [18]. Lean can be defined as an early project planning process for elimination of all non-value added work which is regarded as waste [19]. Delays, waiting, and misused resources are just a few types of waste [20], and all of these can be translated directly to engineering. Lean Project Delivery System (LPDS) is a framework comprising five traditional project phases as triads linked in such a manner to enable cross-functional teams to be involved early in planning and design [21], and is depicted on Figure 2.

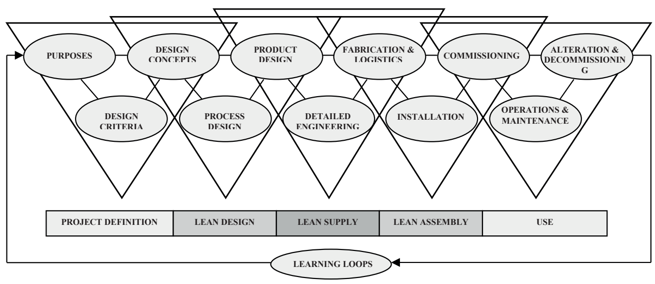

Figure 2. Triads of the Lean Project Delivery System (LPDS) [22]

Utilization of Concurrent Engineering (CE) is advised for dealing with engineering reworks and uncertainty [16]. According to [20], CE is a systematic approach where integrated teams consider more relevant information at the right time for decision-making [19].

Lean design phase is critical due to the following tools and techniques:

- Involve downstream players in upstream decisions, to participate in key decisions [23];
- Share incomplete information for each level of decision making [23], thus enabling CE;
- Selecting alternatives at the last responsible moment, thus reducing negative design iterations as an example of waste reduction [23], providing more time for exploring alternatives [22];
- Shifting early design decisions to a point where they can be made in the most efficient manner [23];
- Consider the influence of installation, logistics, procurement, detailed engineering, maintenance, and commissioning on design [23];
- Reduce batch sizes of information between project participants, thus speeding up design process allowing dividing of decision-making into several segments [23], thus enabling CE;

all for the purpose of designing the final product under the Design for X (DFX) concept, where X marks an ability downstream in the supply chain [23], to achieve a time compression.

Early identification of suppliers and their involvement gives rise to the concept of the Design for Procurability, as designs are to be made with the procurement in mind [23], as the procurement of materials / equipment impacts the detail engineering [24], and it is a critical element for the project success [25]. The design for Constructability [23], focuses on the ease of installation [24], but also on transportability [26]. The supply chain should be involved in the design, construction and in definition of client's requirements.

Figure 3. depicts interrelationships among project requirements and it puts client's requirements with identified requirements stemming out from the supply chain and construction into perspective.

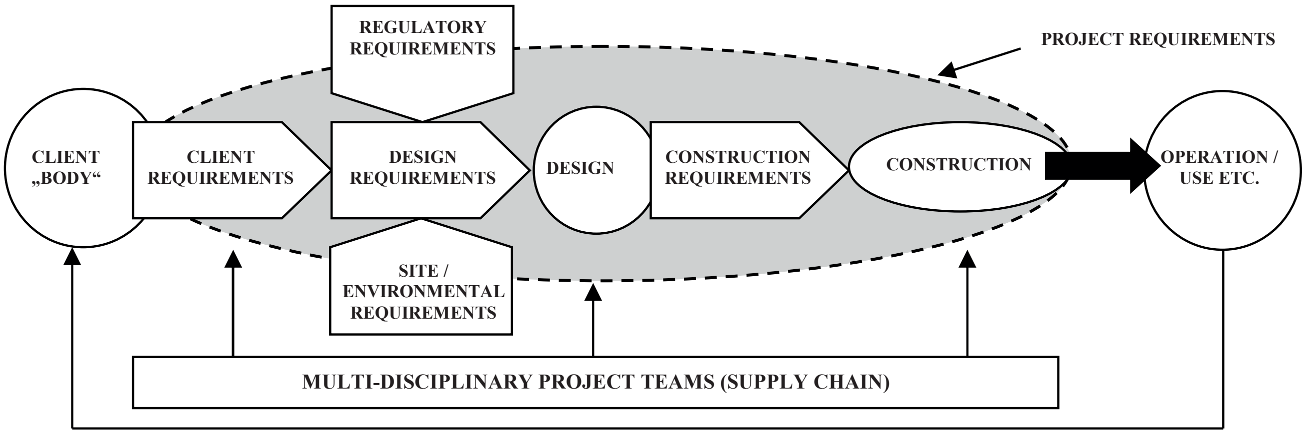

Figure 3. Interrelationships among project requirements [27]

According to Figure 3., the designer needs to translate the "voice of the client" defined inside client requirements successfully into the "voice of the designer" that is aligned with project requirements [27]. In essence, decisions are to be made on what exactly represents client's requirements (seen as a problem), and the representation of those requirements in design terms (seen as the solution) [27].

Less experienced clients tend to provide unclear and ambiguous requirements as input information in the design process [27], increasing design-uncertainty. Satisfaction of all project requirements according to Lean principles becomes a daunting task that requires, according to [19], a high level of engineering effort that is between two to three times higher compared to the traditional non-lean project delivery.

A higher level of required engineering up-front effort in the design process is depicted on Figure 4. as a curve No. 4. The ratio of a higher engineering effort can be extrapolated between curve No. 4 and curve No. 3 during the detailed design stage, as it closely resembles to the ratio between 2:1 and 3:1 as stated earlier.

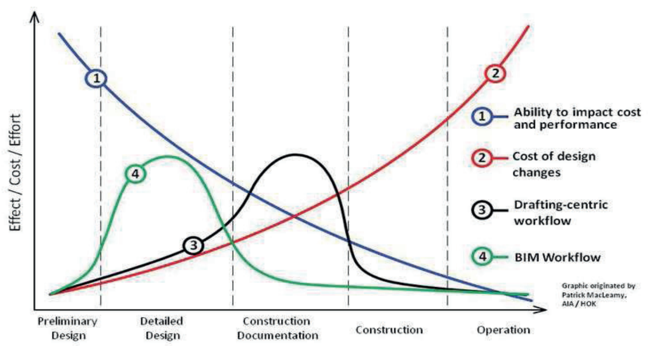

Figure 4. MacLeamy's curve, as adapted from [28]

DESIGN UNCERTAINTIES FROM PRODUCT VARIABILITY PERSPECTIVE

According to Figure 2., the Lean Design comprises both, the process design and the product design. While the process design determines how to produce, the product design determines what is to be produced [23]. Utilities tend to standardize, practicing utilization of standardized specifications and standardized designs [29]. According to [30], standardization is one of the methods of the applied Lean Philosophy that reduces variability. In simple words, the Lean Design is about design standardization reducing variability of potential design solutions, generally enabling reductions in time and cost [30]. However, standardization itself does not guarantee any significant reduction in variability of possible technical solutions, as according to [31]; the range of possible technical solutions can be wide even with standard technical specifications, advising the generation of more thorough and precise specifications even for minor requirements.

Customization is opposite to standardization [30]. In general, and according to [32], Pareto's principle or 80-20 rule can be applied on substations, as "*at least 80% of substation projects can use predefined standardized designs while 20% or fewer will require some form of customization*". Customized designs are referred to as being innovative designs representing tomorrow standards [29].

The decision process is translation of inputs (requirements and constraints) into an output (decisions) [9]. To correlate with Figure 3., all project requirements are treated as inputs into the decision process for the designer as additional constraints, while client's requirements are treated as requirements. Figure 5. is given for that purpose to illustrate the design decision process.

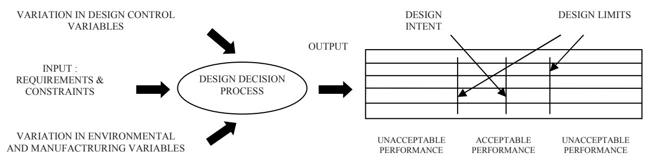

Figure 5. Design decision process in the context of variability [9]

Variation may exist in the form of information fed as an input, but primary variations are stemming out of the design and environmental / manufacturing variations [9]. While design variations can be controlled by affecting design parameters, environmental / manufacturing variations cannot be controlled, as these are based on factory product ranges [9], and they are represented as standard material / equipment properties.

That results in variations around the mean acceptable performance of the design intent [9], and usually involves several acceptable potential product solutions as alternatives [10]. These are designer's preferences that single out one alternative among the others [10], and seek out the best design as a solution following the rule of optimization [10].

PURSUING OPTIMIZATION WITH DECISION-SUPPORT TOOLS

The iterative design process is an example where making of structure decisions is required which is custom to engineering, as a route between the current and a desirable future state comprising multiple nodes of which each node has multiple options to be chosen [33]. According to [34], engineers have been lately forced to make decisions with incomplete sets of information due to time constraints, and rapid decision-making under these conditions represents one of the most difficult tasks for engineers. Calculations are an integral part of the design process for various selections and verifications [35], and engineers preferred to make them only once [36]. Although important decisions need to be made early and they need to be made firmly [24], sometimes decisions are to be made just-in-time (JIT) [37].

In general, the quality of decisions can be improved by utilization of computer-based tools, such as knowledge-based systems (KBS) [9]. KBSs are categorized as decision-support tools [27]. Benefits include a support for key decisions to be made earlier along with an exploration of alternative solutions faster thus streamlining the design process [38]. Streamlining of the design process is also achieved through automation of various engineering calculations ensuring efficiency and accuracy [39].

Three-dimensional (3D) models also enable exploration of alternatives for preparation of more effective designs [40], but also enable reduction in engineering man-hours and thus a faster throughput of projects [41]. Faster throughput of projects is enabled due to the design automation but is also due to rapid evaluation of design alternatives [42]. 3D models are also being referred to as knowledge repositories supporting standardization [43], under which the equipment is grouped into blocks [44], thus further enhancing reusability of same knowledge. In order to benefit from the 3D approach, the process of creating both standardized designs for re-usage and unique designs based on advanced 3D modelling techniques must be automated [42]. Generally, reusing previously captured solutions is a base for "delta engineering" which allows execution of processes starting from specifications to delivery of final documentation, reducing times of engineering tasks through central project database [45]. According to [46], the substation model in 3D can embrace all aspects of the substation project lifecycle, and as such is depicted inside Figure 6.

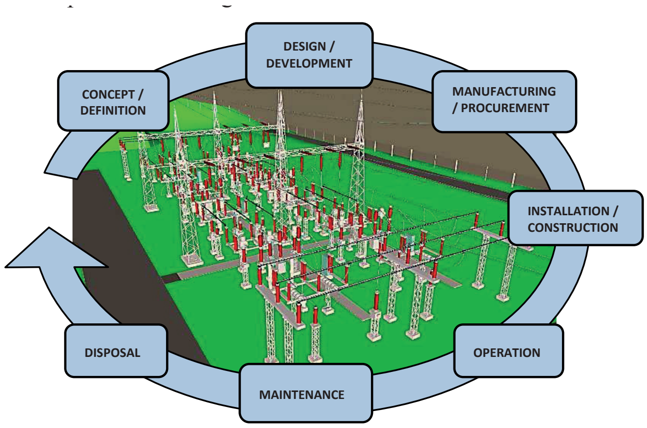

Figure 6. Lifecycle of a substation in a 3D environment with image of El Chaparral station

Building Information Modeling (BIM) is seen as a bridge between decision-support tools as engineering calculations and standardized designs in 3D, with data bases in the background [47].

BIM as "*Building Information Modeling is the development and use of a computer software model to simulate the construction and operation of a facility. The resulting model, a Building Information Model, is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and improve the process of delivering the facility*" [48]. BIM as a Building Information Model is being referred to as a "*shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onwards*" [49].

From a project perspective, BIM stands to enable better decision-making shifting the effort to determine critical cost factors early in the design process [50], as depicted inside Figure 4. as a curve No. 4 compared to a traditional workflow given as curve No. 3. That means that decisions will be made faster and earlier in the process, as making specifications of materials and brand selection can start earlier as opposed to the traditional way to identify suppliers and conducting a pre-selection of brands later on [51]. BIM models comprise "smart" objects containing project-relevant information, among others, calculations [52]. Substation specific calculations can be integrated with 3D substation model, as depicted on Figure 7. Such an approach of having integrated calculations allows analysis and optimization of the design continuously during the entire design and planning phase [50], [53].

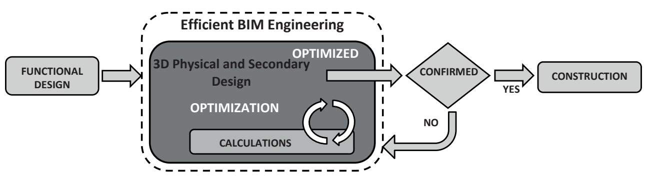

Figure 7. Concept of Efficient BIM Engineering – Integrated Calculations [53]

In general, if performed by a computer, calculations and recalculations are conducted more quickly, allowing further exploration of alternatives [36], and the decision-making is improved through simulations and analyses [54]. BIM therefore could also stand for as a lean framework enabling concurrent engineering, driving agility, and increased accuracy of estimations, designs and calculations with 3D representation defined as a key for engineering decision-making during the entire lifecycle [55]. Decisions are often made, however, without considering of the effects on the project level [56].

DECISION-MAKING MODELS THROUGH THE LENS OF AGILITY

Agility is defined as "*the ability of a system to thrive in an uncertain and unpredictable evolving environment; deploying effective response …*" [57]. The effective response is related to the decision-making and the decision-implementation [58] due to the constantly increasing demand for faster decision cycles [59].

While Simon's model of problem solving is considered to be suitable for engineering problems, it does not include time as an attribute [60], which as a *tempo* or the decision cycle time is a unique feature of Boyd's Observe – Orient – Decide – Act (OODA) decision making model [61].

Faster cycle times in OODA loop are instrumental for perception of the concept of agility [62]. OODA loop is a single-agent model [63], and as such it is fully aligned with the argument that decisions are always made by individuals and individuals alone [10]. OODA loop is depicted as a cycle at the top of Figure 8.

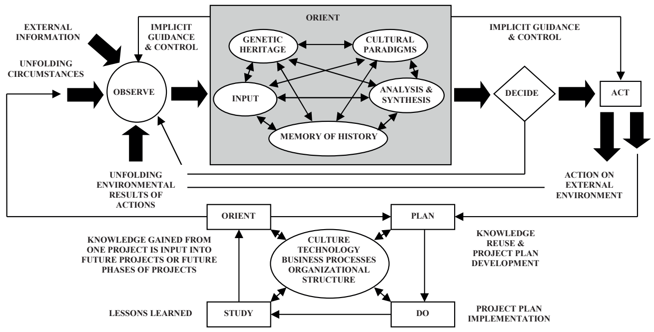

Figure 8. Linked OODA loop and PDSO cycle based on [63] with correction based on [64]

Steps of OODA are described as follows [63]:

- Observe step observe current environment and data / information gathered from both external and internal sources;
- Orient step enable orientation to current situation based on information fed, past experiences and analysis / synthesis for creation of new knowledge and allowing knowledge to be reused;
- Decide step develops hypotheses in order to identify and derive one solution over others, thus representing an identification of a course of action; and
- Act step allows testing of hypothesis by acting on a decision previously made [61].

Main focus of OODA loop is put on the Orient step [61]. It is impacted by employees' keen understanding of the "big picture" [62], or by keeping a broad perspective [63]. It is a "mental thing" [64], shaping observation, decision and action [62].

Knowledge management is one cornerstone of agility [37]. OODA loop lacks planning stage and ability to store / recall data [61]. Remedy is achieved by linking OODA loop with Plan – Do – Study – Orient (PDSO) cycle, thus enabling decision-making cycling for knowledge creation inside OODA loop to be combined with knowledge storage / retrieval within PDSO cycle [63]. PDSO cycle is depicted as a cycle at the bottom of Figure 8.

According to [63], from engineering standpoint, PDSA / PDSO cycling can be described as:

- Plan step for project scoping and developing a project plan along with reusing explicit knowledge from previous projects by means of project documentation;
- Do step deals with implementation of project plan along with reusing both explicit and tacit knowledge from previous projects;
- Study step enables assessment and reflection onto what has occurred in the project and deals with lessons learnt;
- Act step deals with decision whether to reuse previous knowledge on new project or to abandon it.

Act step also represent a link to Observe step of OODA loop for the purpose of orientation whether or not to reuse previous project knowledge, thus PDSA cycle is renamed as PDSO cycle [63].

According to [63], PDSO cycle from a perspective of the project level and the project knowledge:

- Starts with Orient step toward Plan step where specific knowledge is carried
- Knowledge reuse occurs at Plan steps by means of reusing project documentation, from earlier projects thus representing explicit knowledge;
- Knowledge reuse occurs at Do step from previous projects on both explicit and tacit level, including lessons learnt;
- Study steps deals with reflecting and assessing what has occurred in the project;
- PDS steps are related to knowledge flow during project completion or stage completion;
- Knowledge flows from Orient step of PDSO cycle to Observe step of OODA loop.

Operated within OODA loop, information is processed into knowledge (knowledge created) and reused, saving rework [63]. Decisions as such are a commitment to action, but not action itself [61].

Action can flow from two directions, namely from Decide and from Orient through Implicit Guidance and Control (IG&C) link [64]. Later on, one enables more rapid flow as the Decide step if skipped [64], as opposed to the flow form Decide which is required when one is unsure about the course of the action or when there is no plausible action that can be inferred via IG&C link [62].

As a rapid execution of OODA loop is essential for the overall project success [62], this can be achieved in two ways, either using IG&C link and skipping the Decide stage, or speeding up the Decide stage, but for both keeping our observation better matched to the reality is a key prerequisite for both ways [64].

According to [64], different ways of executing OODA loop deal with:

- Usage of existing repertoire of actions directly through IG&C link when faced with low levels of uncertainty, and
- Creating new repertoire of actions through the Decide stage employing a circular process through the feedback of unfolding interaction with environment.

Standardization is seen as a method for creation of repertoires of action from perspectives of both OODA loop and Lean philosophy [64]. A successful organization is described as one being able to employ the existing repertoire, create a new repertoire through circular OODA loop, and update orientations [64].

Figure 8. presents such linked OODA and PDSO cycles based on [63] with deleted input into the Decision from the Implicit Guidance & Control as non-existent according to [64].

A prime example of an Agile enterprise is an Agile Utility. Such an Utility is able to:

- Streamline the design process and automate it [66], [67];
- Standardize the process [68];
- Design in parallel [69], thus employing Concurrent Engineering;
- Define and employ standardized designs for each voltage level [67], [68], thus developing standard layouts [66] and applying it [67], [68];
- Utilize IT [66] through utilizing automated design tools [68] based on 3D models [66];
- Employ designs for procurability and designs for constructability [66] and final solution optimization [68];
- Always looking for more innovative ways to deliver future projects under seemingly impossible time restraints [69];
- Reuse existing standardized designs as a jumpstart for each new project also involving customized configurations [67];
- Form alliances with vendors thus enabling shorter lead-times [66] and cost reductions [68].

According to [57], Agile principles can be incorporated into Lean principles without a compromise. While Lean principles ultimately come down to optimize the project and not its piece [30], and to ensure that once made decisions would never are to be revisited [64], Agile principles ultimately induce the speed and thus, faster response times.

RIGID BUSBAR DESIGN PROCESS, VARIABLES AND CONSTRAINTS

In general, the rigid buswork design process involves selection of the minimum bus size required for ampacity, insulators, hardware, electrical clearance, and determining the short-circuit fault current [70].

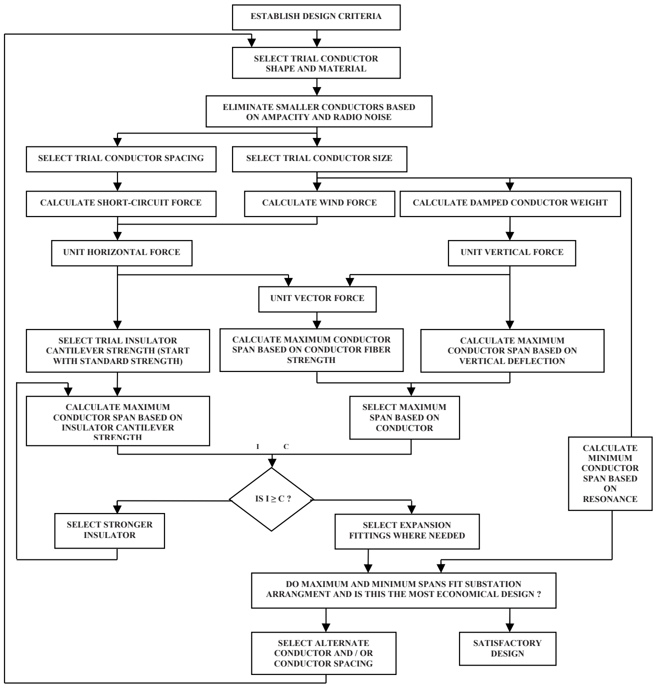

Figure 9. Flowchart for the rigid buswork design process based on [71]

The flowchart of the horizontal rigid busbar design process is given in Figure 9, with a made assumption that the maximum span length is not limited by the aeolian vibration. According to [72], the procedure for rigid bus design is the following : (1) material and size selection based current-carrying requirements, (2) determine bus centerline-to-centerline spacing, (3) calculate the maximum short-circuit force for bus to withstand, (4) determine the total bus conductor loading including environmental factors, (5) calculate the maximum bus span / support spacing, (6) calculate the maximum vertical deflection, (7) determine the minimum required support insulator cantilever strength, (8) provide thermal expansions for conductors, (9) adequately position bus couplers / fittings, and (10) verify the presence of aeolian vibration.

To illustrate a relationship between design variables and environmental / manufacturing variables to constraints, Figure 10 is given representing an interaction of design variables and constraints.

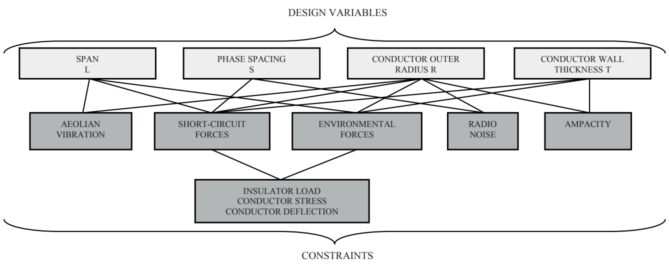

Figure 10. Interaction of design variables and constraints for the rigid buswork selection [71]

Inside the first row of design variables, span and phase spacing are clearly design controllable variables, while the conductor outer radius and conductor thickness are an example of environmental / manufacturing variables, which can be theoretically regarded as uncontrollable if unprocurable, due to the availability of materials that changes from a country to a country [73]. Two bottom rows inside Figure 10 represent constraints for the rigid buswork selection. In the isolation, each of constraints can be easily satisfied [36]. However, the selection of the design variable to satisfy one constraint will not necessarily satisfy other constraints, thus making the rigid buswork design as an iterative process [71], involving excessive calculations [74]. Minimum electrical and structural requirements are usually defined inside company standards [75], and thus they have an anchor in the practice of standardized designs. Standardization can also be reflected into environmental / manufacturing design variables such as the conductor outer radius and its wall thickness being design controllable variables if indeed such materials are procurable, thus further reducing variability on the input side of the design decision process. Customization can be manifested inside Figure 10. as:

An addition of new types of constraints such as physical site constraint [71], and due to upgrading [76] among others;

- Harsher existing types of constraints such as the deflection limit due to aesthetics [77], due to capacity increase [7], and / or due to the new substation location among others;
- A change in one or in all existing design variables, due to upgrading among others [7], [76];
- or it can encompass a new rigid buswork concept such as the A-frame arrangement whose calculations are not covered by relevant standards [78].

All in all, both standardized and customized designs for the rigid busbar selection require undertaking of several design iterations before an optimized technical solution can be identified as the best option.

PROSPECTIVES FOR STREAMLINING OF AN ENGINEERING DECISION-MAKING PROCESS

Reviewing the literature in the previous section, the following has become evident:

- Lean design stage should produce designs that are construction and procurement-driven;
- Design-uncertainties should be dealt up-front for both standardized and customized designs;
- Optimization should be pursued for both product and process design having the project level in mind;
- Design and decision-making processes are complementary and they can be streamlined with BIM;
- BIM is a decision-support tool enabling both Lean and Agile principles to design;
- Agile enterprises utilize IG&C link inside PDSO cycle for deploying existing repertoires of the action based on a range of standardized designs reducing the decision cycle time, while all other companies have to create new repertoires of the action before being able to utilize such an IG&C link;
- Orientation step is the critical step inside the decision-making process;
- Rigid bus system design is a typical example of an iterative process.

The concept model presented on Figure 11 takes into account requirements to include procurability and constructability up-front in the design process, before undertaking a quest for optimization of the functional design. Once optimized and conforming to all project requirements, the functional design is confirmed before its components are ready to be procured and henceforth installed / constructed.

Giving a timely input to design engineers up-front, the following is argued:

- Variation in manufacturing variables is reduced through an early identification of suppliers (perspective of procurability);
- Variation in design controllable variables is reduced through an early incorporation of principles of constructability (which may or may not be grounded into principles of standardization);
- Reduction in variation in both manufacturing and design controllable variables reduces the total number of technical solutions (design alternatives) of the acceptable performance;
- The reduced total number of design alternatives with acceptable performance makes the identification of a best solution easier among the rest based on designer's preferences.

Having integrated calculations incorporated into BIM, the following is argued:

- Time required to single out the best solution is reduced;
- Time required to verify the best solution is reduced;
- Time required to verify any solution is reduced.

While integrated calculations with BIM contribute to agility through speeding up of the verification process by automation and to the selection of an optimized solution from the perspective of the design, lean principles contribute to the time reduction through a filtration of numerous design alternatives by focusing on best suited ones when observed from the project level. A question can be asked regarding possible differences in cycling within a PDSO cycle between an Agile enterprise and other enterprises.

Would such differences be grounded in the standardization and customization? And if they are, how these differences are manifested from a perspective of a decision-making process? What stages of the decision-making process contribute to the final streamlining of a decision-making process? Subsequently, how does this relate to the rigid busbar system design process and from the context of BIM? Answers to these questions shall be put forward by observing *modus operandi* of an Agile Utility as presented inside section 2.4 of this paper, in contrast to the usability test performed on the rigid busbar system design falling under the category of a customized design from the company's perspective.

TUBULAR BUSBAR SYSTEM DESIGN EXAMPLE FROM EL CHAPARRAL PROJECT

The Company ongoing project consists of a 115 kV switching station, El Chaparral, as a greenfield investment and of a 115 kV substation, 15 de Septiembre, as a brownfield investment, both in El Salvador. Both stations are of breaker-and-a-half arrangement.

Some of client's initial design requirements relating to the busbar system of El Chaparral station were ambiguous in regards to:

- Basic Insulation Level (BIL) between 550 kV and 650 kV, representing a parallel requirement for both highest voltage for equipment of 123 kV and 145 kV respectively;
- Aluminum rigid tube properties as Standard Pipe Size (SPS) 3.5 inch was stated but with no other defined requirements relating to its schedule type (outer radius and wall thickness), nor related to alloy type.

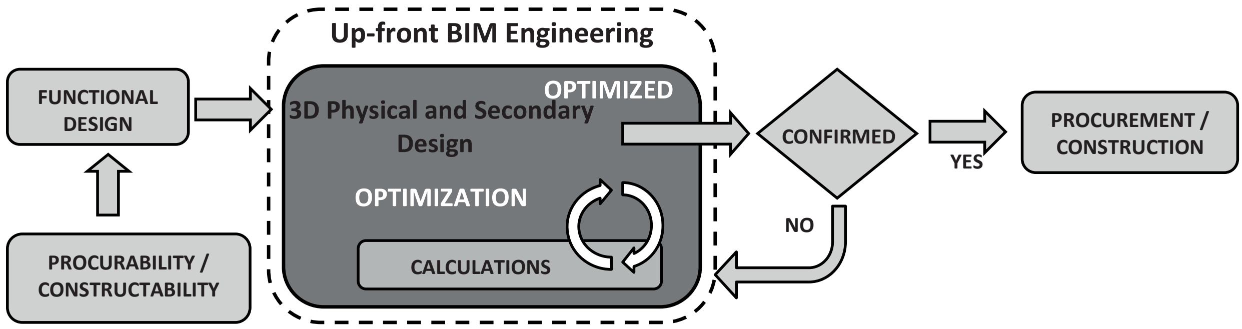

Figure 11. Upgraded concept of Efficient BIM Engineering – Integrated Calculations with timely input regarding procurability / constructability fed up-front

Form a perspective of refurbishment of existing station, 15 de Septiembre, not directly related to the busbar system, following ambiguities were related to:

- A new rigid tube to be installed between two existing 115 kV disconnectors required a rigid tube SPS 2.5 inch, schedule 40 of alloy 6063-T6 type, while electrical DC resistance @ 20°C parameter stated was referring to a SPS 3 inch, schedule 80, alloy 6061-T6 tube;
- No initial requirements for post insulators were stated. However, as existing steel gantries were initially dimensioned as not being able to receive additional gravitational loads of line traps, each new line trap had to be installed on pedestal and supported with additional steel adapter installed between tops of two post insulators. The existing rigid tube goes between these two post insulators slightly beneath the bottom of such a steel adapter while satisfying the minimal phase-to-ground voltage clearance towards the top of the steel support supporting this entire assembly. This solution is depicted in Figure 12. b).

The rigid buswork system at El Chaparral switching station supports currently two diameters and it is depicted in Figure 12.a).

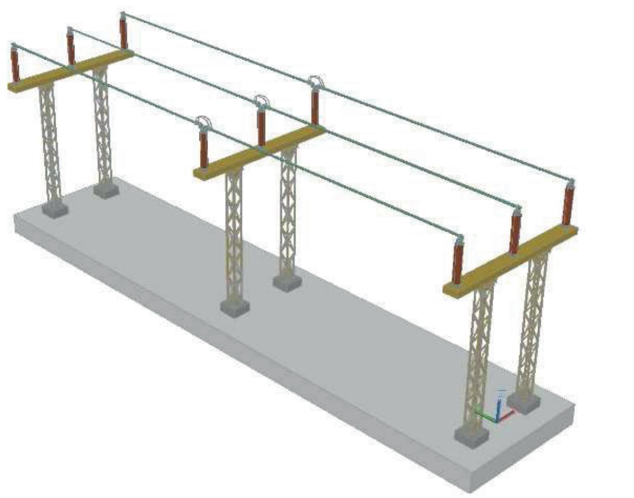

Figure 12. (a) Isometric view of the rigid tubular buswork system, (b) Tubular rigid conductor installed between two disconnectors and going in-between two post insulators for line trap installation

Other atypical client's requirement were related to:

- Standardization of equipment / materials between both stations;
- Steel structure designs to follow the foundation design, as foundations were previously designed by one of Client's subcontractor.

Project requirements were related mostly to procurability of rigid tube conductors according to ANSI H35.2 standard, as suppliers failed to provide exact specifications especially regarding the value of electrical DC resistance @ 20°C parameter. Encountered engineering challenges were related to:

- Inability to timely define procurability of tubular conductors early in the design stage;
- Designing both stations in parallel with definition regarding the installation of line traps and eventual usage of post insulators still lagging behind the design of the buswork system;
- First time dealing with IEEE 605-2008 standard, as all calculations were conducted manually;
- Resolution of the requirement stating BIL 650 kV over 550 kV, thus influencing the buswork system as the tube conductor centerline-to-ground height has increased;
- Downstream steel support engineering required timely inputs for their part of engineering in order to fit in to the previously locked solution for the foundation design.

All of these requirements had put a great deal of pressure on the electrical design engineer (representing up-stream engineering) to make timely decisions in a short period of time whilst limited information of high levels of uncertainty at engineers' disposal. Upstream engineering thus had to be conducted by observing multiple "what-if" scenarios involving calculations and analyses as a part of the multi-iterative design process, before relevant information could be passed downstream.

During upstream engineering decisions were made by following Lean principles of optimizing the project and not its piece, and by ensuring decisions once made are never revisited again from the upstream engineering standpoint:

- Type TR-289 post insulators were specified instead of type TR-286 at both stations, as requirement for BIL 650 kV ultimately prevailed over BIL 550 kV,
- Type TR-288 post insulators were discarded as a solution due a lesser cantilever strength when compared to type TR-286, as type TR-286 post insulators were a strict tender requirement;
- Upgraded version of type TR-289 post insulators were specified with regards to greater permissible tensile, torsion and compression forces;
- All rigid tubular conductors were defined as SPS 3.5 inch, schedule 40, alloy type 6063-T6 over alloy type 6061-T6 due to better volume electrical conductivity at 20°C percent IACS;
- Volume electrical conductivity at 20°C percent IACS for alloy type 6063-T6 inside calculations was fixed at the typical value of 53 as according to IEEE 605-2008, rather than applying allowed value of 55 to be utilized, as allowed by NEMA standard [74];
- Damping rope due to Aeolian vibration was specified on an entire span length, instead on only its two thirds, and of type procurable falling into weight range advised by IEEE 605-2008;
- Clamps / fittings with current links were specified supporting busbar expandability through single spans, therefore concept of continuous busbars was not followed.

In essence, these decisions made aimed at worst case scenario due to weights and forces transferred onto steel structures, in order to pass downstream batches of information relevant for the steel structure design, all for the purpose of both minimizing number of iterations both upstream and downstream, but also for streamlining downstream engineering process. However, even though design variables of span length and phase-to-phase distance (initially already supporting a value of 2.44 meters based on BIL 650 kV as according to [79], [80]) were locked, that still has not relieved design requirement to satisfy all constraints as indicated inside Figure 10., thus requiring exploration of several alternatives including calculations before turning to the validation of selection for both equipment and materials inside the buswork system. Conducting these calculations and generation of subsequent drawings manually proved to be an undertaking wasting engineering resources. Solution for streamlining both the design process and decision-making process has been sought in the meantime by the company, and by following current industry trends, company has acquired "primtech" solution for the smart substation design which was later utilized on entire HV equipment on a station including verification of results on busbar conductor selection as well. "Primtech's" integrated calculations were conducted according to IEC 60865-1 in which the accuracy of calculations has been previously already established. Obtained results confirmed that our designs according to IEEE 605-2008 were on the safe side of the calculation. The most important is that calculations were performed much faster as being automated, thus enabling a faster selection of the best / optimal solution.

DISCUSSION

Drawing on the problem statement brought forward inside Section 3, example of the *modus operandi* of an Agile Utility defined in Section 2.4, and on the described usability test set forth in Section 4 of this paper, this section presents a discussion about relevant questions asked in Section 3 from a perspective of a PDSO cycle.

Agile Utilities are able to use existing repertoires of action skipping the Decide stage through standardized layouts, answering the question whether the current design is the best solution or not. This path is given with blue color inside the Figure 13. All non-Agile enterprises and Agile Utilities dealing with innovative / customized designs must follow an entire sequence from Observe to Act marked with red arrows. In all cases, Act step cannot be skipped as it is related to undertaking of analysis / calculations as a prerequisite for a solution capture and justification.

New repertoires of action are created by cycling within a bigger loop between Observe step and Act step through feedback #2 with possibility of several iterations to be conducted by cycling through smaller loop between Observe and Decide through feedback #1. Once new repertoire is defined as the best solution under required conditions and it is verified through running analysis / calculations, such a solution is saved as a 3D BIM model for future knowledge reuse. Saving a solution as a 3D model applies also to each new reused standardized solution stemming from IG&C link.

Figure 13. presents a new conceptual model of a PDSO cycle based on the depicted one in Figure 8.

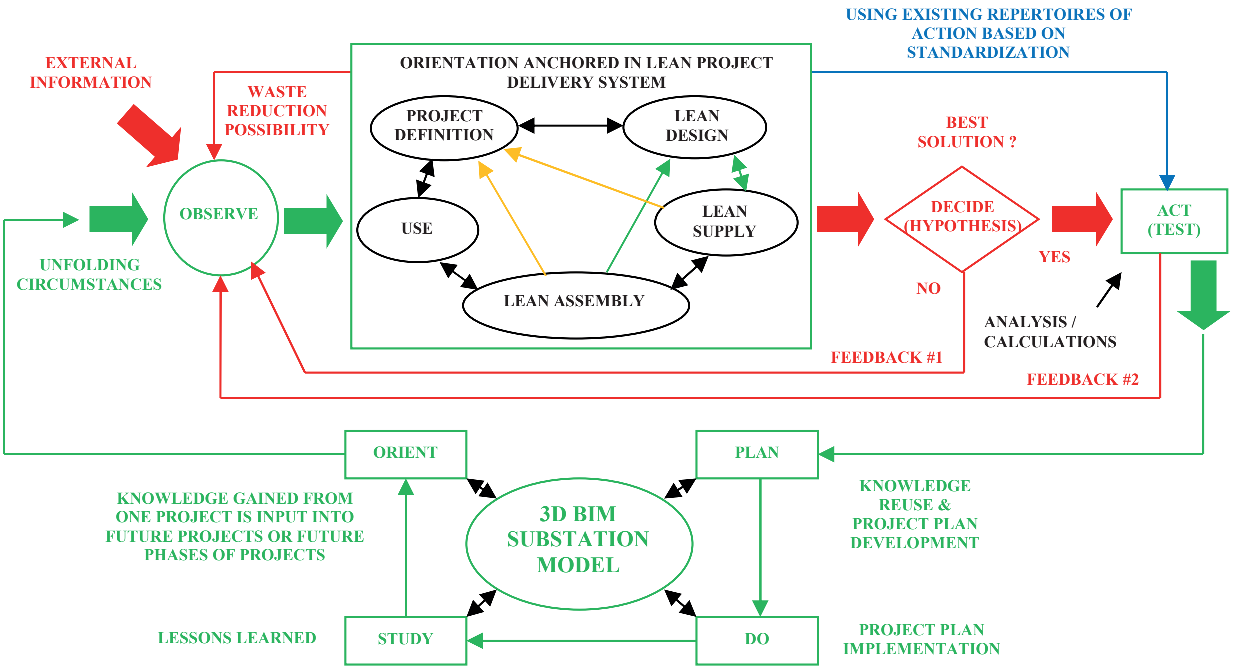

Figure 13. PDSO cycle with indicated differences between an Agile and non-Agile enterprise in respect to the design process based on utilization of BIM models, as adapted from Figure 8.

The Orient step is based on five triads of LPDS. The Lean Design is impacted by the Lean Supply through procurability, and by the Lean Assembly through constructability. These influences are marked with green arrows inside the Orient step. Same can be applied to the Project Definition step of LPDS as indicated with orange arrows. The Orient step as such, and if based on LPDS, enables pro-active search for waste reduction possibilities during the Observe step. The Observe step enables a correlation of design requirements and constraints with project requirements. While design requirements and constraints are fed from the Orient step of PDSO cycle through Unfolding Circumstances, the input enabling constant correlation with project level is fed through External Information input into Observe.

As Figure 13. is defined from a design engineer's perspective, the External information input is a direct correlation to project management through which up-front project related information is being fed. Elements marked with the green color belong to both paths of the repertoire definition / usage.

Streamlining of a decision-making process is conducted through all steps of OODA loop combined with a 3D BIM model as a heart of a PDSO cycle: the Observe step through utilization of the Lean principles, and for the Decide and Act steps through agility due to integrated calculations. The prerequisite for both is a 3D BIM model as a knowledge repository.

CONCLUSION

During Plan, Do and Study steps of a PDSO cycle, knowledge from previous project flows into the new project, meaning that design variables and constraints relevant for buswork design are taken from previous projects as relevant ones during the first iteration. Up-front input must be given from project management level regarding availability of materials / equipment that impact final buswork design. Procurability and constructability concepts must be taken into an account during the design stage. This reduces the total number of alternative solutions, thus faster and more accurate identification of a best optimal solution from a project level is supported. Reduction in number of iterations reduces the number of engineering man-hours required. Through usage of software with integrated calculations, verification of design solutions is conducted much faster and more accurate. Streamlined design process has a direct impact on streamlining of an engineering decision-making process. Streamlined and more accurate information flow is a key for streamlining the engineering decision-making process.

RECOMMENDATIONS

Future papers leaning on this topic could relate to the decision-making for the design of other switchgear parts inside the power substation. Also, future papers could relate to an extension of 3D modeling with BIM in regards to the construction sequencing through utilization of four-dimensional (4D) BIM models (3D space + time), and / or utilization of five-dimensional (5D) BIM models involving 3D space + time + cost as additional dimensions, thus examining the engineering decision-making process from both levels of overall project optimization and design solution optimization.

A. Foškulo, M. Kokoruš, Streamlining the Decision-Making Process on Tubular Rigid Busbar Selection During the Planning / Designing Stage by Utilizing 3D Substation BIM Design Software, Journal of Energy, vol. 67 Number 3 (2018), Special Issue, p. 20–29

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It is often believed that tender requirements correlate fully to client's requirements. However, such a belief is a mistake. Unless tender requirements are fully unambiguous, the client is more likely to hint what it does not want [10]. It is all about finding a best solution among the set of alternatives having sound preferences that trigger the right course of action. That is why engineers are decision-makers and not mere problem solvers [10]. This paper is dedicated to a right course of the action. To dharma.

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