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CRITICAL PATH METHOD AND LEAN DESIGN MANAGEMENT APPLIED IN DESIGN OF SOLAR ENERGY PROJECTS: A COMPARISON STUDY

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***Abstract**: Delays in the construction sector occur frequently in projects and have a major impact on the cost, duration, and quality of the project. Classic management theoretic principles applied, lack of commitment to project management methods altogether with slowing down in the adoption of current technologies could explain problems of project management consisting in frequent project failures. The present research aims to use the lean management method in the construction activity starting with the design management. The paper presents two comparative case studies: the first in the classical management solution and the second using the steps of the lean method, in corroborating the information necessary for: design the installed capacity to produce electricity (photovoltaic solar panels), design their positioning and installation on roofs terrace to existing structures that have undergone various changes over time. In addition, the Investor requested other interventions that required the involvement of several specialists from different fields. Performance indicators were calculated between the two solutions, favorable to the lean method.*

***Key words:** Lean Design Management, BIM, UAV, Photovoltaic design*

1. INTRODUCTION

The construction field is largely fragmented and is well known for reduced performance and productivity as compared to other production sectors. Delays in construction and their effects are the main causes of low performance because they are a common issue at global level [1].

To achieve clients' objectives in the construction projects, it is required that various specialists involve and work together in all the development stages: concept and design, building and exploitation.

Under the high pressure of budget and lead-times constraints throughout the entire design process, there is compensation between multiple and concurrent design criteria, often based on inadequate information. Most design decisions are mutually independent, thus contributing to a difficult management of the workflow among various specialists involved. Moreover, the projects are more and more subject to uncertainty because of the rhythm of technological changes, the rapid change of market opportunities and the pressure to reduce time and costs [2].

The study [3] notice that the greatest deviations of investment costs occur at the level of design management and construction management of the building structures. The authors have presented the 12,4% deviation from the total cost of a project and suggested that the impact generated by the design modifications was 78% of the total deviation, 79% of the costs deviation and 9,5% of the total building cost.

Faulty design management and incomplete elaboration of documentations have been identified as being the major factors responsible of the general deficient performance in various projects that exceed the budget, the established timeframes, and are affected by reconstructing works, variations, and disputes [4].

The recently presented bibliographic analysis by [5] has identified the main issues affecting the interactions among the design teams: 1) communication, 2) coordination, 3) collaboration, 4) trust, 5) delegating responsibilities.

Upon the author's proposal, the development of the classical management solution was replaced with the lean management method, which took in and overcame design shortcomings, gaining the remaking days spent on discussions and changes.

The paper intends to compare performance indicators related to the implementation time of the design solutions and the assessment of the cost reductions resulting from the continuous design coordination in the lean management method versus classical design. In addition, the Last Planner System implementation methodology is presented, supplemented by Building Information Modelling (BIM) and Unmanned Aerial Vehicle (UAV).

2. SYSTEMS AND INSTRUMENTS USED IN CONSTRUCTION MANAGEMENT

2.1 Critical Path Method

The conventional planning practices acknowledge the relations between activities through the Critical Path Method (CPM). However, the main issue with these practices is the deficiency in recognizing the workflow between the tasks, regardless of whether it concerns the transactions flow, the space or resources flow [6].

According to [7], the traditional project management approach is not able to provide an efficient solution to the difficulties in managing the design process. This is due to the fundamental principles of project management, which are based exclusively on the theory of transformation (T) of production – an implicit theoretical model that assesses production only with regard to the input converted into output.

2.2 Lean Design Management

The history of lean management in construction dates back to 1992. The pioneering work was entitled "Applications of the New Production Philosophy to Construction" and was developed by researcher Lauri Koskela who intended to study the application of production techniques in construction engineering, to increase productivity, based on the philosophy of Toyota Production System (TPS) [8].

One step forward to a more solid conceptual base of design and engineering, suggest a simultaneous approach of engineering processes in three ways: conversion, flow and value generation, and the need of a philosophy and management instruments that would fully integrate the concepts of conversion, flow and value.

The instruments and methods developed for the lean management stage of the design have in mind the improvement of the deficiencies related to the defective communication among the interested parties, incomplete documentation for the construction processes, unclear input information, erroneous estimations of resources, overloading the workforce, lack of coordination among various departments and hazarding in decision-making [2].

Several lean tools can be used in lean design, such as target value design (TVD), set-based design (SBD), building information modelling (BIM), choosing by advantage (CBA) [9].

The study of [10] presents the application of the Last Planner System (LPS) and Design Structure Matrix (DSM) techniques within the lean design management in an infrastructure project in UK and presents impressive performance progress and encloses continuous improvement of activities, despite the challenges encountered in the design phase.

2.3 Last Planner System

"Last Planner system of production planning and control is a philosophy consisting of rules and procedures and a set of instruments that facilitate the implementation of these procedures. The system has two components: production unit control and workflow control". LPS can be understood as a mechanism of transforming what SHOULD be done into what CAN be done, thus forming a list of works that are to be performed, based on which weekly work plans can be generated" [11].

The Last Planner system planning cycle consists of four different levels: the general planning level (Master schedule), the Phase planning level, and the lookahead planning level, and finally, the Weekly Work Planning level [12].

The study of [13] presents the use of LPS in a modular offshore wind construction where they observed the reduction of installation time by 36% per Megawatt comparing the results with benchmark values quantified in work-days.

LPS expanded from the construction management to design management, for the purpose of maximizing workforce productivity, resource and material productivity and, in addition, for efficiently managing issues related to the variability of construction projects and workflow smoothness [14].

The project of the Cathedral Hill Hospital in San Francisco emphasizes the importance of planning standardized production and control practices for performance measurement and continuous improvement of processes [15]. LPS applied in the design stage increases the transparency of the design project, the collaboration and communication of design engineers, by improving the workflow stability and reliability [16].

2.4 BIM and Unmanned Aerial Vehicles (UAV)

"BIM is a digital form of construction and asset operations. It brings together technology, process improvements and digital information to radically improve client and project outcomes and asset operations. BIM is a strategic enabler for improving decision making for both buildings and public infrastructure assets across the whole lifecycle"[17].

Design management can be improved by using new instruments and methods introduced by building information modelling (BIM). The study of [18] argues that the use of BIM functionalities supports the Lean Project Delivery System phases.

Moreover, in the design stage the approach of the BIM parametric modelling comes to support the automatic geometrical analyses that contribute to identifying the potential clashes and implementation issues, thus avoiding costly corrective changes and remaking on site. BIM supports new collaborative forms of project deliveries, such as integrated project design, building or delivery [19].

The research by [20] pleads the use of BIM and UAV in quality management along the project implementation.

3. APPLICATION OF CPM AND LPS IN DESIGN PHASE OF PHOTOVOLTAIC PROJECTS

The authors present the application of design management photovoltaic system applied on terrasse roofs, in two management approaches:

- Classic, which created problems in the construction phase (Case study 1)
- Lean management, which partially eliminated the problems in construction phase (Case study 2).

Similarities between the roofs' architecture layouts, the photovolatic panels' support system and the power generated by the photovoltaic system (case 2 is greater than case 1 by 5,74%) has allowed the achievement of the comparative study.

3.1 Description of case study 1

The project is located in Luxemburg and the design and building stages took place in the period of September – November 2020. The installed power of the photovoltaic panel system is 310,30 kWp.

3.1.1 Activity planning and control in the design stage

Resource planning was performed by assessing the project structure, resulting in a list of activities with the corresponding durations and interdependencies. Moreover, critical and non-critical activities were identified, and the calendar schedule of the project activities was represented in the Microsoft Project software through the GANTT diagram.

Multidisciplinary design solutions have been based on checklists distributed among the parties involved and on phone conversations.

3.1.2 Roof measurements and CAD 2-D design

Prior to the design stage, manual measurements were taken in order to validate the dimensions of the two roofs. Site measurements were processed in 2-D digital format and later sent to the photovoltaic panel system designer. The design stage was completed in 21 days.

3.1.3 Design changes and inconsistencies

The construction activities were interrupted by inconsistencies between the positioning of the photovoltaic panels and existing mechanical installations. In addition, the "lifeline" safety and security system was installed after the designer's visit, thus not being included in the design stage. The changes occurred in the execution project included re-designing and repositioning a number of 74 photovoltaic panels. Moreover, it was necessary to develop a list of updated materials that included the project changes.

The implementation of the updated solution required 6 days to complete.

3.2 Description of case study 2

The project is located in the central area of Amsterdam, in the Netherlands, and was carried out in the period of November 2020 – January 2021. In addition to the limiting conditions related to space and worksite organization, another peculiarity of the project consisted of:

- the simultaneous execution of roof renovation of 3 residential buildings of different height,
- restoration and installation of new ventilation equipment,
- development of new photovoltaic panel system fitted on the roofs, with 328 kWp power installed.

3.2.1 Last Planner System

The management of the design activities was based on lean management concepts, instruments, and techniques. Activity planning with Last Planner System in the design stage included: the master schedule, the lookahead schedule defined for a period of 2 weeks, the weekly work planning, and the measurement of the performance indexes together with the identification of the causes generating deviations.

In completing the LPS, we implemented the BIM model integrating the 3 disciplines: civil construction design, installations, and the new photovoltaic panel system. Prior to the BIM integrated model, we performed a drone inspection of the location in order to generate the real dimensions of the working areas.

a) Collaborative planning

Given that the conditions of the Covid-19 pandemic have limited physical meetings, a hybrid session was organized, using Microsoft Teams online platform but also included physical presence of the members belonging to the same team. The participants list included designers of civil constructions, photovoltaic panels, and MEP, as well as the investor, his specialized consultant, project managers, worksite supervisors and team leaders of the three disciplines.

The collaborative session concluded by establishing the project objectives and generating the master schedule composed of 26 independent activities. The information discussed in the session was transpose to a Microsoft Excel worksheet. Moreover, we analyzed the overlapping of the planned activities and improved the sequence by developing the Reverse Phase Schedule. A part of the document is presented in Tabel 1.

Table 1

Project milestones worksheet

Milestones	Planned week	Requester	Performer	Status	Due Date	Constraints	Reason for variance
Define project objectives Building 1, 2, 3	Week 1	All Contractors	Owner	RL	15.11.20	Pergola design under Investor decision	Owner: change orders
Drone inspection	Week 2	Owner	All Designers	RoT		Legal regulations to use drones	
Roof spatial dimensions, interferences, evenness of roof areas	Week 2	Owner	All Designers	RoT			
Integrated BIM model	Week 4	Owner	All Designers	RL	25.11.20	BIM coordinator requested	Owner: change orders
Delivery of execution drawings	Week 5	Owner	All Designers	RoT			

b) Make – Work ready planning

The make-work ready planning was a systematic and collaborative process of identification and elimination of constraints pre-established within the collaborative meeting. The analysis of constraints was performed in 3 different ways presented in Figure 1:

- RoT (Removed on time),
- RL (Removed Late),
- O (Open).

The status of activities and constraints defined in the collaborative session was updated weekly, by each team involved, thus reducing the variables occurred throughout the project and minimizing the waste generated by rework.

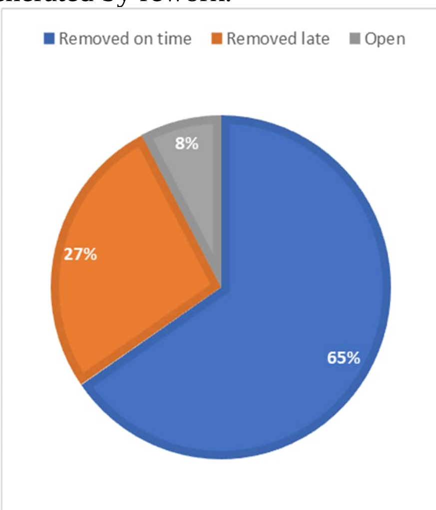

Fig. 1. Constraints analyse

The efficiency of the activities carried out by the three design teams was assessed weekly, by calculating the ratio between the completed activities and the activities promised throughout a week, expressed in percentage – defined in Lean Management as Percent Planned Complete (PPC) [11]. Figure 2 shows the calculated values of PPC during the design implementation.

Moreover, for a continuous improvement of the planned activities, we have identified the causes that led to delays in completion. The main causes identified were the “changes in design” and the “delays in decision making” in relation to the “design approval” of technical documentation by the Investor. The LPS implementation duration in the design stage was 22 days.

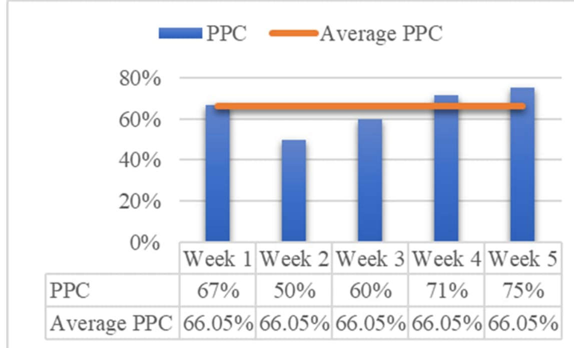

Fig. 2. PPC calculation

c) Drone inspection

The drone inspection of the object of interest consisted of taking 223 aerial images and computerized processing through the algorithm called structure derived from a moving sensor (SfM - Structure from motion) using the Pix4D software.
The 3D model resulted in the textured solid model and digital surface model (DSM), the digital elevation model (DEM), together with the orthophoto mosaic presented in Figure 3, which was used to generate roofs spatial dimensions. Following the data processing, the spatial dimensions were included in the design activities.

It is worth mentioning that the image captures lasted 17m:57s, while the generation of the DSM and the orthophoto mosaic 12m:21s.

Inspection methodology:

- Drone type: quadcopter model DJI Mavic Pro
- Camera type: digital camera FC330 12MP, 4000 x 3000 (RGB)
- Inspection altitude: 50 meters from the subject
- Photographing direction: nadiral
- Flying path: predefined points
- Image processing: computerized processing by applying the SfM algorithm and deriving the 3D high resolution model.

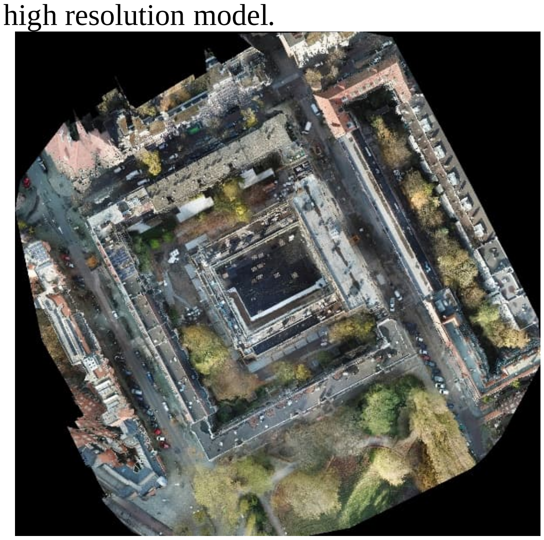

Fig. 3. Orthophoto mosaic representation

d) BIM implementation

The overlapping of the roof renovation activities, installation of envelope materials, installation of the new ducting system and the photovoltaic panels required the analysis and identification of the physical interferences (clash-checking), presented in Figure 4.

Fig. 4: Interdisciplinary coordination on Roof 3

Moreover, the BIM model was used to evaluate the static performance of the elements subject to their own weight load, wind load and snow load.
One of the influencing factors for the photovoltaic panel system is the shadowing during the entire life cycle of the system. By BIM modelling we simulated the natural light and shadowing throughout the entire day, thus eliminating the defective positioning of the photovoltaic panels right from the design phase.

The authors developed an illustration of estimated savings developed by using BIM to avoiding rework due to design mistakes in Table 2, which includes overlaps of the newly designed installations with the existing skylights and stairwells, and the lifeline system with the new photovoltaic panel system. The shading calculation was performed by using the PVSol software, being a function of geo-localization of the site, module power, inclination angle and cost per kWh.

Table 2

Estimated savings by using lean management supplemented by BIM

Identification number	Overlapping construction elements	Number of similar positions	Roof	Estimated cost avoided	Estimated rework/unit	Unit	Coordination Date
COL_R_01_MEP_001	Ventilation pipe	34.00	Roof 1	28,560.00 €	14.00	hours	Week 4
COL_R_01_Civil_001	Skylight	3.00	Roof 1	6,300.00 €	35.00	hours	Week 4
COL_R_02_MEP_001	Ventilation pipe	15.00	Roof 2	12,600.00 €	14.00	hours	Week 4
COL_R_02_Civil_001	Staircase	2.00	Roof 2	6,600.00 €	55.00	hours	Week 4
COL_R_03_MEP_001	Ventilation pipe	16.00	Roof 3	13,440.00 €	14.00	hours	Week 4
COL_Lifeline_001	Life-line system	-	Roof 1, 2, 3	16,200.00 €	90.00	hours	Week 5
SHADOW_R01_PV_001	PV shadow (80% efficiency)	341.00	Roof 1	3,057.51 €	99625.47	kWh	Week 5
SHADOW_R02_PV_001	PV shadow (80% efficiency)	252.00	Roof 2	2,087.23 €	92029.39	kWh	Week 5
SHADOW_R03_PV_001	PV shadow (80% efficiency)	168.00	Roof 3	927.66 €	61352.93	kWh	Week 5

The ability to rapidly generate the quantities of necessary materials for the construction works by using BIM has contributed to the assessment of the alternative design scenarios. With regard to the photovoltaic panel system, on Investor request 4 alternative scenarios were developed, with different generated powers.

The design requirements were aligned with the needs defined by the Investor and materialized by adopting the final design solution, based on collective decisions also involving the teams responsible of constructability aspects.

4. DISCUSSIONS, LIMITATIONS AND RESEARCH OPPORTUNITY

The comparative analysis of the two case studies presented in Table 3 highlights the improvements on multiple levels in the design stage by implementing lean design management:

- The collaborative structure allows the control of variability in the initial design;
- Reliability of planning and easy adaptation of changes requested by the Investor;
- Continuous improvement in lean management allowed a better flow of activities taking into account both initial and subsequent design constraints.

The calculation of the key performance indicators support the benefits of applying the lean design management method:

(1)Design time spent per unit of installed system power = days spent ÷ system power;

(2)Cost variance = total realized cost – total planned cost;

(3)Project schedule performance = planned days ÷ realized days;

The calculated values are presented in Table 3.

The main limitation of the application of lean design management is the resistance of the parties regarding the adaptation of lean principles in close connection with the lack of knowledge of lean philosophy. Moreover, the natural inclination towards a hierarchical structure and decision-making was observed separately by specialists.

To streamline of the application of lean design management, the authors highlight a number of research opportunities as follows:

- Cultivating lean principles within organizational structures through trainings prior to collaborative sessions;
- The application of LPS together the Control Room (Obeya) was limited by pandemic conditions. Using an integrated digital tool might facilitate and shorten the weekly meetings;
- Complementing the drone inspection with the application of Augmented, Virtual and Mixed Reality solutions to improve the visualization of the solutions proposed by the designers and mitigate change orders.

Table 3

Comparison of case study 1 and case study 2

	Case study 1	**Case study 2**
Organizational management	▪ Hierarchical structure, command and control	▪ Team-based structure, collaborative decisions
Number of specialists involved	▪ 6, organized in “silos”, decisions made separately by specialists	▪ 6, weekly collaborative sessions
Design management and instruments and technology integration	▪ Traditional: CPM, Gantt Chart (Microsoft project), 2-D CAD, manual roofs survey	▪ Lean management: LPS, BIM 3D, UAV, roof survey based on drone inspection
Risk management	▪ Reactive, based on past facts	▪ Proactive, systematic process of removing constraints
Design duration	▪ 21 days + 6 days rework	▪ 22 days
Performance measurements	▪ Checklists	▪ Percentage Plan Complete
Key performance indicators (KPIs):		
Time per unit produced	▪ 0.087 days/kWp	▪ 0.067 days/kWp
Cost variance	▪ + 17,280 €	▪ - €
Project Schedule performance	▪ 77%	▪ 100%

5. CONCLUSIONS

The comparison between two case studies with similar construction specifications and generated power that is higher by 5,74% in case 2, has led to the following conclusions:

- The lean management method reduced the design duration by eliminating reconstruction works in the implementation stage of the photovoltaic panel system;
- The time indicator per system installed power was 77,01% in report to the classical management solution;
- The variation of the design realized cost and the planned cost has a positive value (over-budget) in the case of the classical method, because of supplementary time due to reworks (6 days).

The purpose of adopting the lean design management and implementation of BIM is a new approach to the design instruments with a transforming power not only on the design process, but also on the building process on the whole. In addition, it allows overcoming the current constraints, leading to the continuous improvement of the project performance.

The presented lean instruments proved to be useful in eliminating waste and constraints occurred in the project structure.

Authors present the applied lean design management methodology:

- Measuring space dimensions of the roof by drone inspections;
- LPS implementation: organizing collaborative sessions and the involvement of the installation team in the design phase;
- Multidisciplinary integration by adopting BIM.

With regard to the implementation drawbacks of the presented methodology, authors have found:

- Purchasing the drone and piloting it in urban areas requires specialized training;
- Management education for designers;
- Cultivating lean philosophy within organizations (extensive use of these instruments requires adopting the lean culture in the company’s strategy).

The use of the Last Planner System offers support to project managers in order to comply with the undertaken deadlines and to define the project input data flow accurately, systematically organize internal processes and for a proactive control of the output data.

As per the authors’ knowledge, there weren’t any scientific papers identified presenting the LPS implementation in the photovoltaic systems’ design. Moreover, the presented study can be used as a basis for extrapolating lean management in the implementation of the photovoltaic panels.

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METODA DRUMULUI CRITIC ȘI MANAGEMENTUL PROIECTĂRII LEAN APLICATE ÎN CONCEPȚIA PROIECTELOR DE ENERGIE SOLARĂ: UN STUDIU DE COMPARAȚIE

Rezumat: Întârzierile în sectorul construcțiilor apar frecvent în proiecte și au un impact major asupra costului, duratei și calității proiectului. Principiile teoretice clasice ale managementului aplicate, lipsa angajamentului față de metodele de management de proiect, împreună cu încetinirea adoptării tehnologiilor actuale, ar putea explica problemele managementului de proiect constând în eșecuri frecvente ale proiectelor. Prezenta cercetare își propune să utilizeze metode de lean management în activitatea de construcții începând cu managementul proiectării. Lucrarea prezintă două studii de caz comparative: primul în soluția clasică de management și al doilea folosind etapele metodei lean, în coroborarea informațiilor necesare pentru: proiectarea capacității instalate de producere a energiei electrice (panouri solare fotovoltaice), proiectarea poziționării acestora și a montajului pe terase acoperiș la structuri existente care au suferit diverse modificări de-a lungul timpului. În plus, Investitorul a solicitat și alte intervenții care au necesitat implicarea mai multor specialiști din diferite domenii. S-au calculat indicatori de performanță între cele două soluții, favorabile metodei lean.

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