VDC management in the industrialization process using prefabricated reinforcement cages. Case Study: Ovalo Monitor Bridge

Alejandro PALPAN[1*], Sandra VEGA[1], Felipe QUIROZ[1], Mark VICUÑA[1,2], Rodrigo TUESTA[2] and Alexandre ALMEIDA DEL SAVIO[2]

[1] *TSC Innovation, Peru*
[2] *Civil Engineering Department, Universidad de Lima, Peru*
[*]*Corresponding author's e-mail: apalpan@tscinnovation.com*

ABSTRACT
Reworks and delays in production processes are commonly found in construction projects associated with a low level of industrialization and a lack of design constructability. To promote industrialization, improve project constructability, and reduce the execution time, we implemented the Virtual Design and Construction (VDC) methodology. An industrialization strategy was established using a prefabricated reinforcement cages system (PRC) elements in an 870-meters bridge construction project in Lima, Peru. The objective was to improve the project buildability with high industrialization of the steel rebar works. We replaced the traditional on-site cutting and bending steel reinforcement processes with an industrial process that integrates construction management with the supply chain through Building Information Model (BIM). As a result, the level of industrialization of the PRC elements of the bridge substructure and superstructure reached 85% and 40%, respectively, aligned with a 16% execution time reduction of the project.

KEYWORDS
VDC, BIM, bridges, industrialization, prefabricated reinforcement, supply chain.

INTRODUCTION
Traditional construction systems can imply unnecessary expenses and loss of resources, either in labor or in materials and tools, which can affect the quality of the project (Penadés Martí, 2002). For this reason, humans have always sought to improve and optimize each process they carry out, eliminating waste. Construction is one of those processes subject to several changes and revolutions (López Flores, 2018). In recent decades there has been a growing interest in construction industrialization. Qi et al. (2021) mention that industrialized construction integrates design and optimization tools to solve complex challenges in construction projects. The most discussed benefits are productivity improvement, cycle time optimization, as well as a reduction in lead time and costs. They also mention that industrialized construction still faces obstacles to implement and adapt within the construction sector. There is still a lack of communication, a lack of quality inspection systems for manufacturing and installation activities, and poor supply chain efficiency (Qi et al., 2021). To overcome the problems associated with the increase in the level of industrialization, it is necessary to reduce the typical variability in construction projects, for which it is important to use appropriate management methodologies to improve processes, generate collaborative environments and make efficient use of information technologies.

Prefabricated reinforcement cage (PRC) elements

Prefabricated Reinforcement Cages (PRC) are essential for precast concrete elements and, therefore, the construction industry. According to Simonsson and Emborg (2007), approximately 50% of the total construction cost of a bridge infrastructure comes from reinforcing steel and in-situ concrete pouring, and comments that from an ideal theoretical point of view, the time reduction can reach up to 80%. This means that implementing construction methods that reduce time and costs is essential to maximizing project profitability. Pre-assembled elements are generally done off-site. Final placement is the only on-site task to be carried out (Espinoza Conislla, 2012). Thus, outsourcing of the steel item increases productivity, quality, and safety and reduces costs, construction time on site, and labor inspection (Devine et al., 2018).

According to Acevedo Díaz (2009), in traditional construction, the cutting, bending, assembly and installation of reinforcement bars are done manually by steel fixers. The alternative of pre-assembling the steel bars in a workshop allows the overlapping of activities and saves time in construction. Moving these activities from the site to an industrial area will help reduce the labor works on-site compared to traditional systems. (Espinoza Conislla, 2012). Devine et al. (2018) found through a qualitative survey that the work time of the workforce for the mooring of the bars is reduced by 27% when the prefabrication of the elements is carried out. But once the additional time consumed in transporting the pre-assembled components (transportation from the supplier to the factory and then from the factory to the construction site) is considered, the total savings are reduced to approximately 1-14%.

On the other hand, Maciel and Corrêa (2016) state that deficiencies in the fabrication and pre-assembly shop may be related to poor management, communication, and information exchange between stakeholders: designer, builder, and supplier. Therefore, it will be very important to establish processes that allow integrating the construction management and the supplier's supply chain by efficiently using information technologies under a collaborative environment.

Virtual Design and Construction (VDC)

At the beginning of the 21st century, the Center for Integrated Facilities Engineering (CIFE) at Stanford University introduced the VDC methodology. This is known as the use of multidisciplinary models in different design-build projects, the work processes, and the organization of the design-build-operation team, including the product, to achieve business objectives (Kunz, J., & Fisher, M., 2020). The VDC methodology is presented through an implementation framework with its three components: ICE (Integrated Concurrent Engineering), BIM (Building Information Modeling) and PPM (Project Production Management). Metrics and controllable factors are identified for each component to efficiently evaluate and control performance during project development. (Majumdar et al., 2022). The projects developed with VDC seek to reduce variability with optimal processes based on Lean and production physics (PPM), technologies such as BIM, cloud connectivity allow to provide the necessary data for the people involved to collaborate with each other (ICE). In this way it is possible to optimize production and construction processes to accelerate the level of industrialization in construction projects.

METHODOLOGY

This research is based on a qualitative and quantitative approach. A bibliographical literature review was carried out based on academic papers which matched the keywords of the present research work. A theoretical perspective was built to measure the variables in the data collected from a construction project. The VDC methodology was implemented, and the industrialized components (PRC) were adopted for a bridge construction project (case of study). We analyzed the production metrics to identify the industrialization benefits and concluded them based on the VDC framework.

Project description - Case Study

The case study is based on the Ovalo Monitor Bridge Project located in Lima, Peru. Information related to the bridge construction project has been compiled from the contractor and the steel suppliers (Figure 1). The project has a length of 2.2 km, of which 870 m correspond to the main structure; composed of the bridge and access ramps.

Figure 1. Ovalo Monitor Bridge project, Lima-Peru (TSC Innovation, 2022)

Description of the problem

Since the project's right of way is in a central and highly crowded area, the works should be well planned to avoid traffic disruption during the project construction. The Municipality of Lima plans to reduce 85% of the vehicular flow with the commissioning of the bridge; hence there is great importance in completing the execution of the bridge in the shortest time possible. The builder presented the challenge of carrying out the construction in the most efficient way possible. However, he found that the basic engineering (technical file) contemplated various deficiencies, interference with water pipes and sewage, etc. The reinforcing steel item presented a high complexity due to the particular geometry of the bridge. The storage area is narrow and limited to the right-of-way boundary. The original working schedule was e considered a traditional construction method without considering any industrialization related to the steel rebars. The conventional approach resulted in low productivity in the steel assembly. High demand for the labor required for the on-site execution process was estimated.

Strategy for Industrialization using VDC

Initially, it was necessary to analyze and map the process to identify the main restrictions and critical factors to optimize the construction process of steel rebars. Reinforcing steel was recognized as one of the most incidental and restrictive items, so the analysis focused on improving production management by defining an optimal process that required industrializing the project. Various optimization analyses were carried out to configure and assemble the different construction parts (PRC) in each project component (Footings, Columns, Header Beams, Deck, etc.) to substantially improve the expected result assembly time of steel in situ. This was carried out through a VDC implementation framework defining as main objectives the effective reduction of the project execution period and the completion of the work by April 2022.

Objectives were defined for each VDC component, developing a BIM engineering (LOD 400) for production, that can be buildable and industrialized. This engineering considers the main constructive variables of the construction process through an effective strategy that connects the model information to the production chain, efficiently integrating the teams involved through ICE sessions. Additionally, defining controllable factors and monitoring production metrics improve decision-making during construction management.

RESULTS AND DISCUSSION

According to the VDC methodology, it was necessary to have measurable objectives defined according to the needs of the project and the client. Likewise, goals should be defined for each component (BIM, ICE, PPM). As a result, a VDC implementation framework was obtained for the Ovalo Monitor Bridge project (Figure 2).

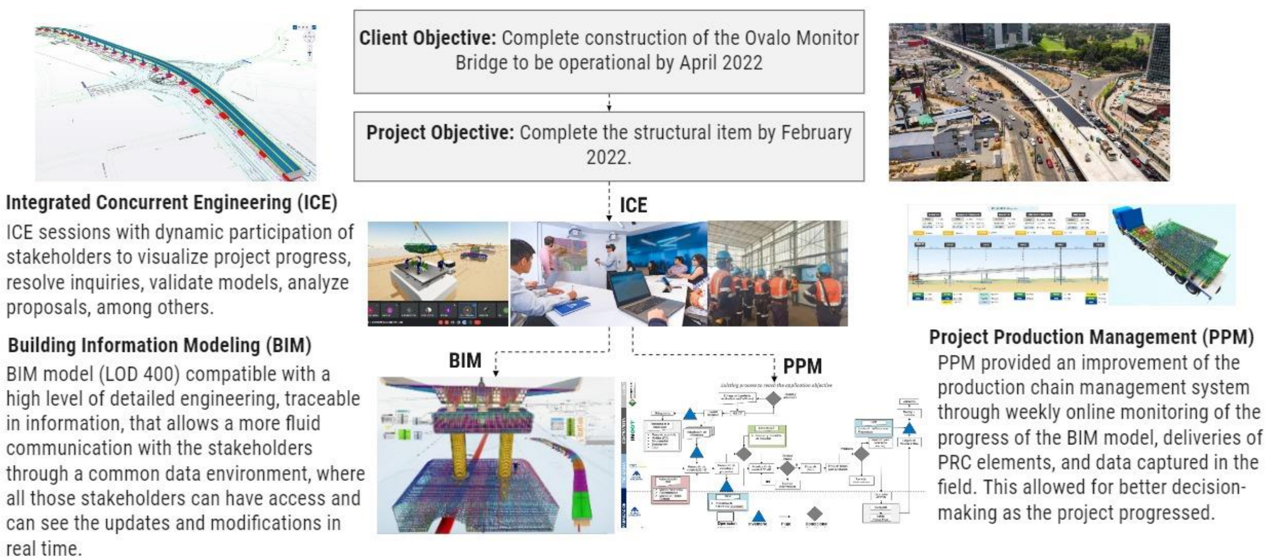

Figure 2. VDC Framework proposed for the Ovalo Monitor Bridge project (own elaboration)

Following the objectives presented in the VDC Framework, production metrics (PM) and controllable factors (CF) were proposed to monitor the VDC implementation (Table 1). The results include monitoring carried out from May 2021 to March 2022 (11 months). Continuous analysis was carried out to obtain more precise data and improve decision-making during the implementation process.

Table 1. Production metrics (PM) and controllable factors (CF) (own elaboration)

Objective	Metrics	Goal
PM_ICE: Facilitate and integrate the activities and tasks of the teams involved in charge of the project (delivery of PRC elements).	%PAC = # Activities completed / # Total activities to be completed x 100	> 80%
PM_ICE: Fulfillment of the commitments agreed upon at each ICE meeting.	Fulfillment of commitments	100%
CF_ICE: Promote the participation of all teams involved in each ICE session.	% Attendance at each ICE session	100%
	Frequency of ICE sessions	1 per week
PM_BIM: Perform a BIM model integrating multiple disciplines.	%RFI's solved	100%
	% Structures preassembled with QA/QC	100%
CF_BIM: Define LOD to be used.	Minimum LOD required	LOD 400
PM_PPM: Increase the level of industrialization of reinforcing steel assembly by 75%.	% of industrialization	≥ 75%
CF_PPM: Make value propositions of the PRC to the client to understand its advantages.	N° of constructive simulations using PRC for each Structural Typology	≥ 2 / each structure
CF_PPM: Follow up on weekly progress	# Weekly progress monitoring review days	1 per week

***PAC:** Percentage of activities completed* ***RFI:** Request for information*
***QA/QC:** Quality assurance / Quality control* ***LOD:** Level of development*

As part of PPM, multiple mappings of the process were developed with the stakeholders to define the critical factors for the implementation, the most outstanding aspects of the process were identified, which included the optimization of the design, development of a industrialized model using elements made in the workshop (PRC) to improve fieldwork (Figure 3).

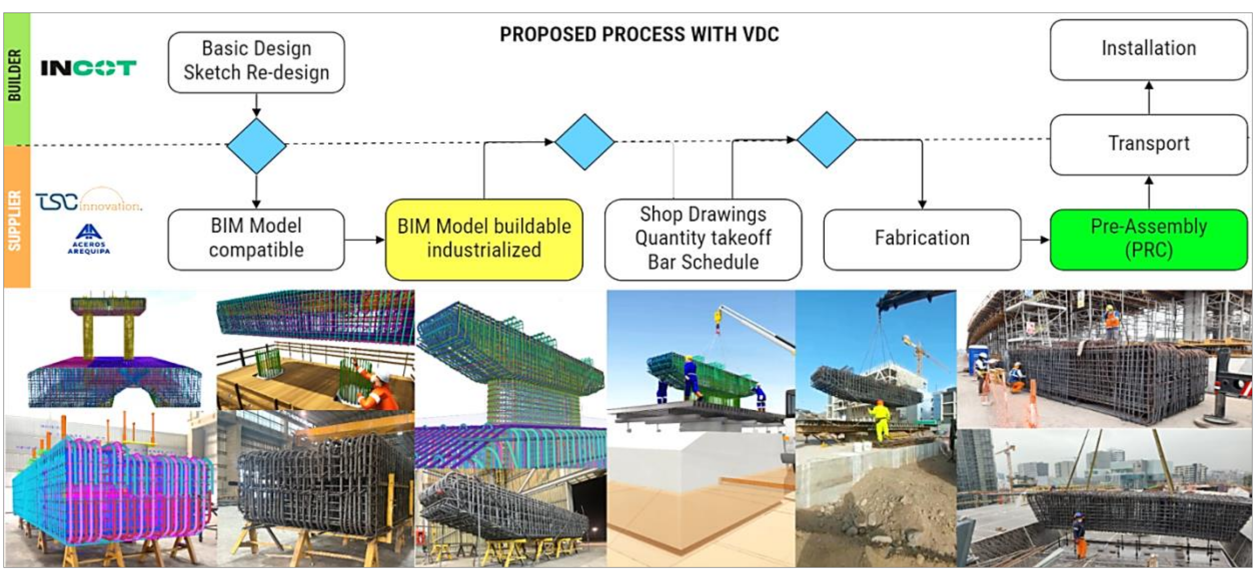

Figure 3. PPM, Simplified production process - Industrialization with PRC.

On the other hand, information technologies were vital to integrating stakeholders in the project's development—the BIM model incorporates multiple disciplines. The BIM elements have attributes that allow better control of the project online, ensuring the traceability of the information. A LOD 400 was applied for manufacturing reinforcing steel. It was possible to efficiently connect the PRC information to the production system generating various uses in each stage of the process (Figure 4). Several proposals were made to improve the design based on modularization and optimization analysis of the construction process, which was reviewed and validated by the stakeholders in the ICE sessions. Establishing a common data environment (Trimble Connect) helped visualize the model and construction process simulations.

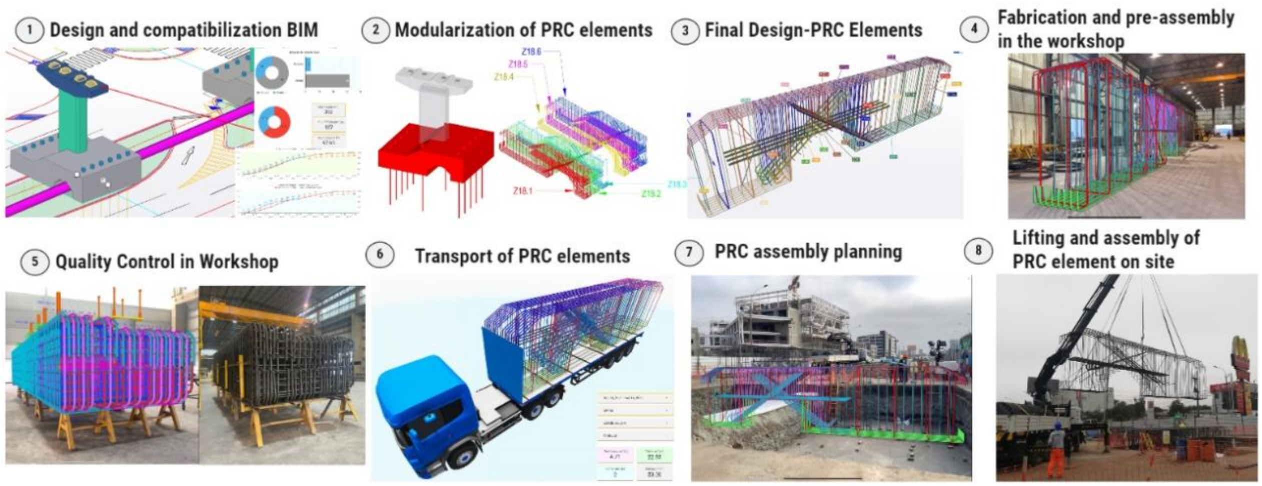

Figure 4: Production process of PRC

Table 2 shows a follow-up at each control milestone defined during implementation, which allowed observing, analyzing, and predicting the project's behavior.

Table 2. Tracking of Production Metrics (PM) and Controllable Factors (CF) (own elaboration)

Component	Metrics	M1	M2	M3	M4	M5	M6	Target Value
CO	%Reduction Time	6%	9%	12%	13%	15%	16%	>15%
PO	%Rebar Reduction Time	5%	10%	15%	24%	27%	31%	>25%
ICE	PAC	76%	79%	80%	81%	83%	86%	> 80%
BIM	% RFI's solved	43%	64%	92%	93%	95%	100%	100%
PPM	% Industrialization	18%	34%	38%	59%	68%	72%	≥ 75%

The industrialization of the bridge was the most critical aspect, so the pre-assembly of 75% of the bridge in the workshop was a very ambitious goal. As a result, an industrialization rate of 85% was obtained for the substructure (footings, piers, header beams). For the superstructure (slabs, diaphragm beam, etc.), 40% industrialization was achieved, as it was much more complex due to the linear configuration of the elements. Likewise, 72% industrialization was obtained for the overall bridge (Figure 5a). At the same time, figure 5b graphs the progress of the project vs. time. The baseline represents the progress of the project without the implementation of the VDC or the use of PRC. The real progress of the executed project is also observed, in which a percentage was obtained of time reduction of 16% which is equivalent to 40 calendar days.

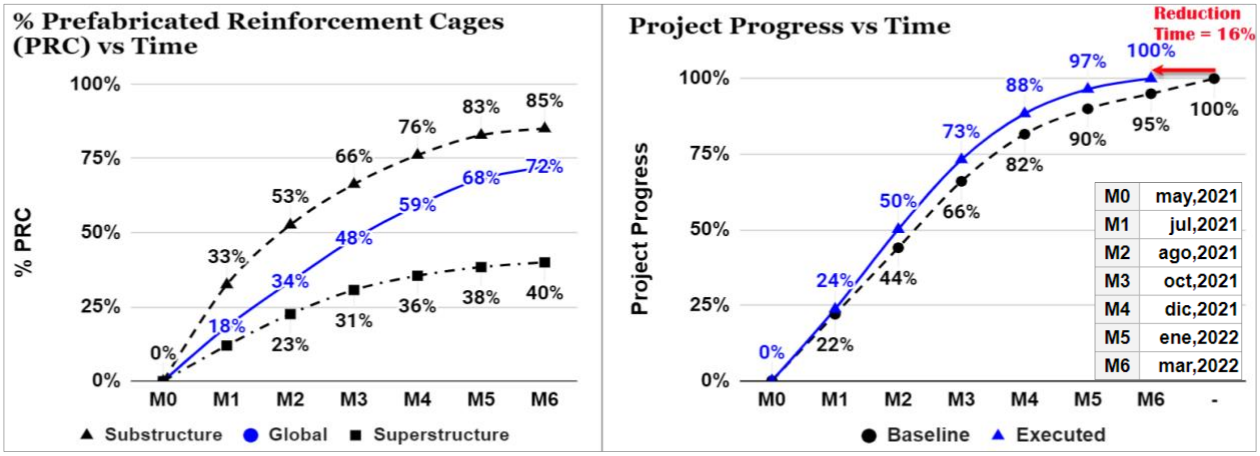

Figure 5: (a) %Industrialization with PRC vs Time (b) Project Progress vs Time

CONCLUSION

The results discussed in this research showed that the VDC methodology, in conjunction with the industrialization of the structural construction process, allows improving productivity and reducing the time frame of a construction project. As it was in the case study of the Ovalo Monitor Bridge, where a time reduction of 30% was achieved in the installation of the steel batch by using PRC elements and consequently a 15% reduction in the overall execution time of the structural batch was obtained, thus exceeding the range of time savings (1% -14%) of prefabricated reinforcement, proposed by Devine et al. (2018).

To carry out the achievement of project and client objectives, it was necessary to design the production processes to obtain a significant time reduction in the steel batch, this was carried out through an industrialization process using PRC elements. The industrialization level obtained was 85% and 40% for the substructure and superstructure, respectively, as well as an overall industrialization of 72%, achieving satisfactory results.

The BIM model allowed the development of several construction improvement analyses using PRC elements, as well as a high flexibility to changes and accuracy of each bridge component for its subsequent fabrication and assembly. Active stakeholder participation was generated during the ICE sessions to quickly resolve RFIs, propose constructability improvements and obtain early validation of the model to reduce uncertainty during the workshop assembly and on-site assembly processes. PPM improved the production chain management system that allowed to analyze, predict, and correct deviations in construction through weekly online monitoring of the progress of the BIM model, deliveries of PRC elements, and data captured in the field. This allowed for better decision-making as the project progressed.

Lastly, the implementation of industrialized construction methods accompanied by an appropriate project management methodology that focuses on the design of the production process, integrates stakeholders, and uses efficient information management, can substantially improve productivity in the production chain and reduce lead times compared to traditional approaches.

ACKNOWLEDGMENTS

We want to thank the TSC Innovation, Incot and Aceros Arequipa for providing us with the necessary resources and information to complete this research.

REFERENCES

Acevedo Díaz, C. A. (2009). Evaluación técnico económica del uso de armaduras prefabricadas en Chile [Technical and economic evaluation of the use of prefabricated armor in Chile] [Thesis, Universidad de Chile]. Universidad de Chile Institutional Repository. https://bit.ly/3924foC

Devine, R. D., Barbachyn, S. M., Thrall, A. P., & Kurama, Y. C. (2018). Effect of Tripping Prefabricated Rebar Assemblies on Bar Spacing. Journal of Construction Engineering and Management, 144(11), 04018099. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001559

Espinoza Conislla, J. M. (2012). Elaboración y colocación de vigas pre-armadas como alternativa de mejora frente al armado tradicional de vigas [Elaboration and placement of pre-assembled beams as an alternative to improve the traditional assembly of beams] [Thesis, Universidad Nacional de Ingeniería]. Universidad Nacional de Ingeniería Institutional Repository. https://bit.ly/3EhoT2L

Kunz, J., & Fischer, M. (2020). Virtual design and construction. Construction Management and Economics, 38(4), 355-363. doi:10.1080/01446193.2020.1714068

López Flores, L. E. (2018). Análisis y evolución de los sistemas constructivos prefabricados, impacto ambiental e interacción con el sistema constructivo tradicional mexicano [Analysis and evolution of prefabricated construction systems, environmental impact and interaction with the traditional Mexican construction system]. Anales de Edificación, 4(3), 44–51. doi: 10.20868/ade.2018.3799

Maciel, A. R., & Corrêa, F. R. (2016). Interoperability with IFC in the automated rebar fabrication. ISARC 2016 - 33rd International Symposium on Automation and Robotics in Construction, 872–880. https://doi.org/10.22260/ISARC2016/0105

Majumdar, T., Rasmussen, S. G., del Savio, A. A., Johannesdottir, K., Hjelseth, E., & Fischer, M. (2022). A comparative analysis of production metrics across VDC implementations. Construction Research Congress 2022. https://doi.org/10.1061/9780784483978.104

Penadés Martí, J. (2002). Construcción Industrializada de Edificios [Industrialized Construction of Buildings]. España. https://doi.org/10.3989/ic.2002.v53.i478.625

Qi, B., Razkenari, M., Costin, A., Kibert, C., & Fu, M. (2021). A systematic review of emerging technologies in industrialized construction, Journal of Building Engineering, 39, 102265, ISSN 2352-7102, https://doi.org/10.1016/j.jobe.2021.102265

Simonsson, P., & Emborg, M. (2007). Industrialization in Swedish bridge engineering: A case study of Lean Construction. Proceedings IGLC-15. https://bit.ly/2X2KdaV