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# EVALUATION OF CONSTRUCTION PERFORMANCE WITH THE USE OF LPS AND PRECAST SLABS IN RESIDENTIAL BUILDINGS

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## ABSTRACT

The implementation of the Last Planner System (LPS) and off-site construction has been identified as means to improve production management and, thus, increased productivity and project performance. Nevertheless, the sector lacks an evaluation system that allows clients, designers, and contractors to identify areas for continuous improvement and encourage further adoption of the LPS and off-site manufacturing. Therefore, this paper aims to analyze performance during the construction of the reinforced concrete structural frame of two similar high-rise residential projects in Lima-Peru. Both projects used the LPS. However, the first case used traditional on-site poured slabs, and the second used a mix of precast slabs and additional on-site pouring. Data was collected during the construction process and included labor data, production data, schedules, site visits, and observations. Data were analyzed to obtain cycle times, production and productivity rates, and labor density. The results show that the building using precast slabs performed 14% better in terms of time and 16% in terms of productivity compared to the traditional slab. Further research can measure performance and productivity by implementing other precast components such as shear walls, beams, and columns.

## KEYWORDS

Last Planner System, Off-site construction, performance measurement, productivity, Lean Construction.

## INTRODUCTION

Globally, the construction industry has grown just 1% per year over the past two decades, and this is reflected in the lagging productivity, skilled labor shortages, and unpredictable

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materials costs (McKinsey & Company, 2020). This results in low project performance, cost overruns, and execution times more than planned (McKinsey & Company, 2020). In Peru, building construction exhibits traditional processes such as onsite formwork and concrete pouring that have been the norm for many decades. However, the transition from traditional methods to precast structural components is a major task. The construction sector is well known to be reluctant to change. For example, the penetration of innovations such as Building Information Modeling (BIM) has been slow. One of the reported reasons for the lack of adoption is the little evidence of the relative advantage of adopting such innovations. Ultimately, senior managers and decision-makers require evidence before making investment decisions. Therefore, performance must be evaluated, reported, and continuously updated to drive change. Furthermore, technological advances in the production of precast elements have expanded the possibilities for faster, more sustainable, and high-quality construction, with designs and applications that respond to the challenges of contemporary buildings.

Lean Construction (LC) aims to minimize the waste of materials, time, and effort while generating maximum value for the customer (Khalife & Hamzeh, 2020). The application of lean methods and tools has reported benefits such as organizing an improved production system, increased productivity, and improved occupational health (Howell et al., 2017). Bertelsen and Koskela (2004) argued that LC contains five main principles: specify a value for the customer, identify value stream, make value flow, pull value, and pursue perfection through continuous improvement. The Last Planner System (LPS) is the LC's method for production planning and control. LPS divides the planning system into four levels; the master schedule, the phase schedule, look ahead planning (LAP), and the weekly work plan (WWP). The LPS focuses on reducing uncertainty and variability in the process workflow, including the management tools such as the Plan Percent Complete (PPC) and the Reason of Non-Compliance (RNC). PPC measures the performance of the planning system (i.e., the number of completions divided by the number of assignments for a given week). RNC investigates the root cause of non-compliance in the PPC to learn from repeated failures and prevent their repetition in the future (Ballard & Tommelein, 2021). In addition, it has been shown that there is a correlation whereby the earlier the PPC is controlled, the higher the probability of a successful project and the lower the RNC (Lagos & Alarcon, 2020). Moreover, a collaborative contract with key subcontractors is pivotal to ensuring continuous flow during LPS implementation (Murguia et al., 2016; Khalife & Hamzeh, 2020).

Some existing body of literature has studied performance improvement because of the use of LC and prefabricated components. For example, some studies have shown that the implementation of Lean Construction serves to control, plan, and execute work in the field, presenting itself as an efficient solution to improve productivity, meet deadlines, and safety management (Verán & Brioso, 2021; Ballard & Tommelein, 2021). On the other hand, some studies have analyzed the benefits of using prefabricated components together with BIM and standardized processes. These studies have found increased performance in construction, such as reduced rework, reduced lead time, and better productivity (Xiaosheng & Hamzeh, 2020; Schimanski et al., 2021). Nevertheless, existing literature does not contain quantitative performance metrics. Therefore, the lack of performance information in construction is considered a problem in the industry. For this reason, the main objective of the research is to comparatively evaluate two residential projects implementing the LPS. However, one project has implemented precast slabs, whereas the other project has used traditional in-situ slabs. The results might provide evidence of the performance improvement through the combined adoption of LPS and precast components.

# LITERATURE REVIEW

Previous research has reported that the implementation of lean construction methods such as the LPS, Kanban System, Just in Time (JIT), and prefabrication have contributed to improved project performance (Xing et al., 2021). However, the industry lacks a consistent performance measurement framework to benchmark project performance across the construction industry, identify common targets and assess performance improvement due to the adoption of innovations (Murguia et al., 2022). Furthermore, the trend in the construction industry is to integrate lean construction with prefabrication and BIM to achieve increased productivity (Saieg et al., 2018). Additionally, lean construction and prefabrication have been studied to analyze energy consumption and carbon emission reductions (Heravi et al., 2020). It is claimed that prefabrication reduces onsite inventory and allows continuous on-site workflow and waste minimization (Tam & Hao, 2014). Another significant advantage is that prefabricated components can allow flexibility in design by tailoring to desired shapes and dimensions as required (Richard et al., 2019). Furthermore, it is highly recommended to have a supplier that manufactures precast elements with a lean production approach. Lean capacity and capability can be assessed by the contractor to ensure collaboration and a balance between the factory supply and onsite demand. The synergy between the manufacturer, the labor subcontractor, and the contractor must be incorporated into collaborative contracts to achieve the desired performance (Murguia et al., 2016).

Prefabrication of components requires a holistic supply chain management which includes optimizing the design, production, storage, transport, and installation of the precast elements, in addition to improved coordination between the interested parties (Phang et al., 2020). Previous literature suggests that there are positive results of the implementation of LC and off-site construction by implementing lean tools through simulations in the manufacturing process (Darwish et al.,2020). However, it is more focused on the off-site production in factories as reported by Ballard et al. (2003) and Sacks et al. (2003). The proposed recommendations focused on restructuring the production plant in cells rather than distinct departments. Also, they suggested reorganizing functions with an emphasis on workflow, rather than resources, to reduce lead times and minimize waste.

However, there is a lack of studies focusing on performance measurement with the collective use of production management principles such as LPS and off-site construction. On the one hand, the construction industry is complex and data across projects is not standardized and cannot be used for useful comparisons (Costa et al., 2004). On the other hand, there is not a significant number of studies showing production and productivity metrics that can be used for national or international benchmarking. For this reason, the current research aims to provide key project performance indicators of projects using LPS and off-site construction. This would be a valuable contribution that can trigger the report of performance data of similar projects.

# METHODOLOGY

To achieve the proposed objectives, this study has selected a case study. A case study is an empirical inquiry that investigates a phenomenon (i.e., the case) in depth and within its context, especially when the boundaries between the phenomenon and the context may not be evident. As such, the main research questions are “how” or “why” questions, the researcher has little control over the behavioral event, and the focus of the study is contemporary as opposed to a historical phenomenon (Yin, 2014). Qualitative and quantitative data were collected in two high-rise residential buildings in Lima, Peru which were under construction between 2020 and 2022. The types of data collected were the start and end day per level, m2 of gross external area, quantities of concrete (m3), formwork (m2), reinforced steel (kg), and the number of workers per crew. Based on Murguia et al. (2022), the following indicators were established: cycle time (days), the production rate (m2/day), labor productivity (m2/mh), and the density of labor (m2/worker). These metrics are in line with the research aim which intends to provide evidence-based project performance because of the implementation of the LPS and off-site manufacturing.

T-tests were selected as the statistical tool to find significant performance differences between the two projects. Both buildings are comparable as they have the same structural frame of reinforced concrete, have a similar footprint area, and use the same construction technology. The study collected data daily during the erection of the main structural frame. Three main activities were included in the data collection process: (1) rebar installation; (2) formwork and (3) concrete pouring for both vertical (columns and shear walls) and horizontal (beams and slabs) elements. The cost metric (Total cost/m2) was not selected as a performance indicator as the cost between both systems is similar. However, a potential reduction of time translates into economic benefits due to reduced overheads. In addition, there are wider benefits for the client and investors as reduced project time improves the return on investment.

# CASE STUDY DESCRIPTION

Project A is a high-rise residential building consisting of 4 basements and 18 stories. The construction of the main structural frame started in January 2020 and was hit by the outbreak of the COVID19 pandemic in mid-March 2020. However, the works resumed in June 2020 and the structural frame was finished in September 2020. Project B is a high-rise residential building consisting of 4 basements and 20 stories of the construction of the main structural frame project started in November 2021 and finished in February 2022. Project A has a traditional construction with all structural elements being poured in-situ. However, project B has implemented precast slabs that consist of a thin precast element (5 cm.) which acts as a slab itself and substantially reduces the propping system and the concrete pouring. Also, the precast slab includes the sagging rebar which also reduces the rebar installed on site. As a result, the crews install the hogging rebar and pour the reduced volume of concrete. Figures 1 and 2 show images of projects A and B. Also, Table 1 shows a summary of the project's characteristics.

# RESULTS

The Last Planner System was implemented in tandem with takt-time planning in both projects. Each level was divided into some locations and a pull system was designed to ensure continuous flow among crews and activities. The takt-time plans (TTP) were designed with a takt equal to one day as shown in Figure 3. Plans were designed considering five days a week; however, the construction sites operated half a day on Saturdays. Thus, time buffers were included in the plans. Project A was divided into four zones whilst project B was divided into three zones. Project B was split into lower zones due to the ability to install precast slabs at a higher speed. The divisions were made to ensure similar quantities for rebar, formwork, and concrete pouring in all zones. Figure 4 shows the division of zones on a typical floor plate on Projects A and B. Project B exhibited more complex logistics due to the JIT delivery, and vertical movement with the crane to their final position.

Table 1: General Information of Projects A and B

| **Project** | **A** | **B** |
|---|---|---|
| Use | Residential | Residential |
| Location | Lima | Lima |
| Structural frame | Reinforced concrete | Reinforced concrete |
| Number of levels | 18 + Rooftop | 20 + Rooftop |
| Basement area (m2) | 4,260 | 3,446 |
| Building area (m2) | 11,880 | 13,118 |
| Type of slab | Traditional | Precast |

Figure 1: Project A - traditional propping system for slabs

Figure 2: Project B - Precast concrete slabs

| | Takt Production System Project A | Day | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Item | Activity | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | Vertical rebar (Columns and Shear Walls) | P1S1 | P1S2 | P1S3 | P1S4 | | | | |
| 2 | Embedded MEP in vertical elements | P1S1 | P1S2 | P1S3 | P1S4 | | | | |
| 3 | Vertical formwork | | P1S1 | P1S2 | P1S3 | P1S4 | | | |
| 4 | Vertical concrete pouring | | P1S1 | P1S2 | P1S3 | P1S4 | | | |
| 5 | Beam formwork (base) | | | P1S1 | P1S2 | P1S3 | P1S4 | | |
| 6 | Beam rebar | | | P1S1 | P1S2 | P1S3 | P1S4 | | |
| 7 | Beam formwork (sides) | | | | P1S1 | P1S2 | P1S3 | P1S4 | |
| 8 | Slab formwork | | | | P1S1 | P1S2 | P1S3 | P1S4 | |
| 9 | Slab rebar | | | | | P1S1 | P1S2 | P1S3 | P1S4 |
| 10 | Embedded MEP in slabs | | | | | P1S1 | P1S2 | P1S3 | P1S4 |
| 11 | Slab concrete pouring | | | | | P1S1 | P1S2 | P1S3 | P1S4 |
| 12 | Slab concrete finishing | | | | | P1S1 | P1S2 | P1S3 | P1S4 |

| | Takt Production System Project B | Day | | | | | |
|---|---|---|---|---|---|---|---|
| Item | Activity | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | Vertical rebar (Columns and Shear Walls) | P1S1 | P1S2 | P1S3 | | | |
| 2 | Embedded MEP in vertical elements | | P1S1 | P1S2 | P1S3 | | |
| 3 | Vertical formwork | | P1S1 | P1S2 | P1S3 | | |
| 4 | Vertical concrete pouring | | P1S1 | P1S2 | P1S3 | | |
| 5 | Beam formwork (base) | | | P1S1 | P1S2 | P1S3 | |
| 6 | Beam rebar | | | P1S1 | P1S2 | P1S3 | |
| 7 | Precast slab propping | | | P1S1 | P1S2 | P1S3 | |
| 10 | Precast slab placement | | | P1S1 | P1S2 | P1S3 | |
| 11 | Embedded MEP in slabs | | | P1S1 | P1S2 | P1S3 | |
| 12 | Slab rebar | | | | P1S1 | P1S2 | P1S3 |
| 13 | Slab concrete pouring | | | | P1S1 | P1S2 | P1S3 |
| 14 | Slab concrete finishing | | | | P1S1 | P1S2 | P1S3 |

Figure 3: Project A and B production systems

The construction technology is described as follows. First, the vertical rebar is placed. Then, the formwork for vertical elements is installed and this is followed by the concrete pouring of columns and shear walls. After the vertical element's erection, the beam's rebar and formwork are placed. Also, the plumbing and electrical system are installed before the concrete pumping. This is followed by the slab formwork, slab rebar, and slab concrete pouring. Project B has changed some steps of this process due to the precast slabs. The system needs a substantially reduced propping system which is installed before the precast slabs are placed in position. Slab hogging bars are then installed and finally, concrete is poured for the remaining slab thickness.

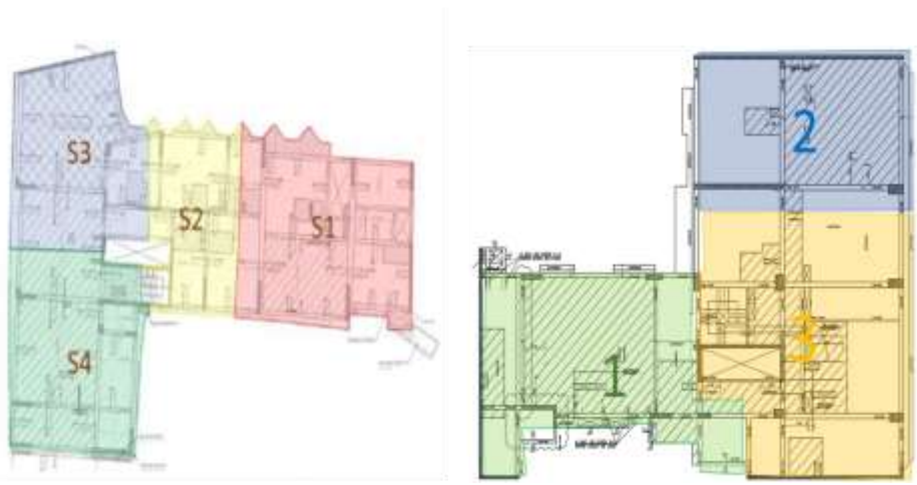


Figure 4: Division of zones for projects A and B

Despite the best efforts to design a continuous flow and to remove restrictions, there was variability due to power supply problems, crane logistics, lack of personnel due to COVID19, inoperative concrete pump, and crane installation. The collaborative sessions with foreman and subcontractors served as a platform to reduce variability. The PPC was recorded as shown in Figure 5. In projects A and B, the PPC accumulated was 88%. Furthermore, as the figure shows, the variability in project B was less in comparison to project A PPC.

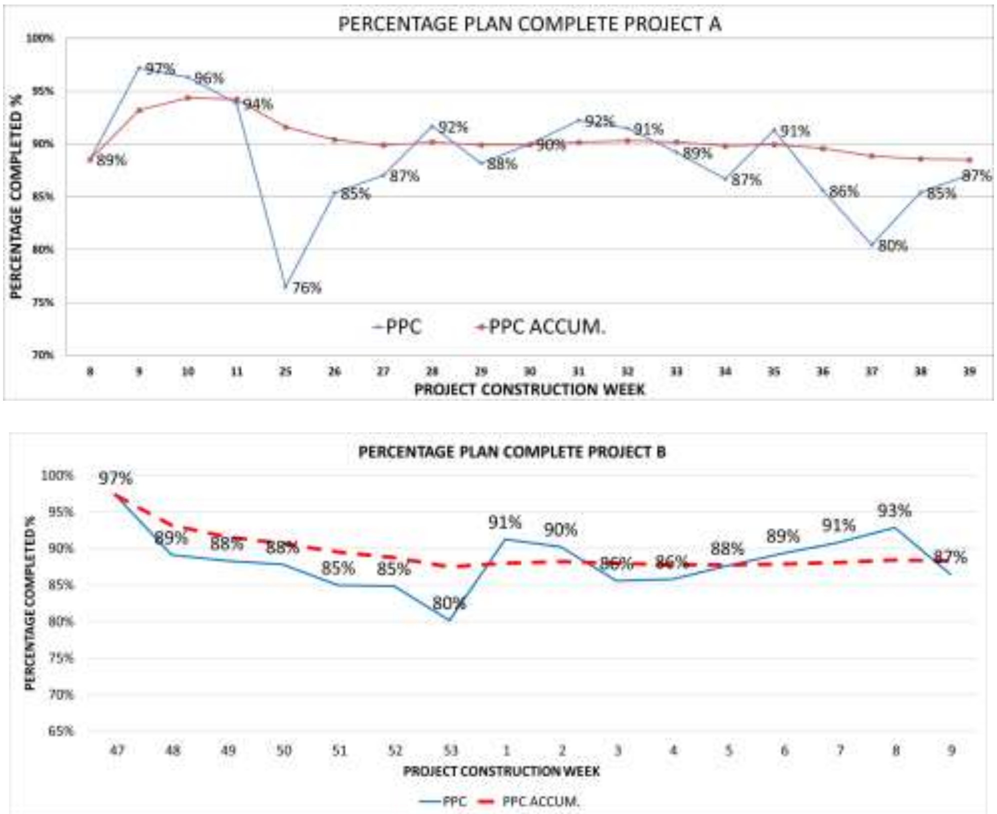


Figure 5: A sample of the PPC of Projects A and B

Table 2 presents a summary of the performance indicators selected for this study. First, the cycle time for each floor was calculated, considering the installation of the vertical rebar of the first zone as the start day, and the slab concrete pouring of the last zone as the end date. The cycle time for Project A was 9 days on average whereas it was 7 days for Project B which means a 29% reduction. Second, the production rate (m2/day) per level was also calculated. T-Test was conducted and found a significant statistical difference ($p<0.001$) between 63 m2/day in Project A and 73 m2/day in Project B. Globally (from level 1 to the top floor), the performance was 123 m2/day in Project A and 135 m2 in Project B. This global performance improvement is due to the takt-time planning that allows overlap between schedules at consecutive levels. Third, the productivity measured in m2/mh was estimated at 0.25 m2/mh for Project A and 0.30 m2/day for project B. T-test was conducted and there is a significant difference between the two projects ($p<0.001$). It should be highlighted that this calculation does not include the hours used by MEP workers (electricians, plumbers, etc.). Traditionally, these services are embedded within the slabs in Peruvian buildings. However, we have dropped these hours to allow for international comparisons. Finally, there was not found a significant difference in the density of workers onsite which is explained by the transformation of only one structural element. It would be expected to have fewer workers/m2 when more components are prefabricated.

Table 2: Summary of performance indicators for Projects A and B

| Project | A | B | Difference |
|---|---|---|---|
| m2 per level | 565 | 500 | -13% |
| Cycle time per level(days) | 9 | 7 | -29% |
| Total man-hours (mh) per floor | 40,684 | 33,600 | -21% |
| Production rate - per level (m2/day) | 63 | 73 | +14% |
| Production rate - global (m2/day) | 123 | 135 | +9% |
| Productivity (m2/mh) | 0.25 | 0.30 | +16% |
| Density (m2/Worker) | 8.19 | 7.81 | -5% |

# DISCUSSION

The results suggest that the implementation of precast slabs has a better performance compared to the traditional system in terms of time and productivity. The use of precast slabs required collaborative work between the main contractor, the manufacturer, and the crews as it requires a Just in the Time production system and more complex logistics. It has to be acknowledged however that it was not possible to get off-site manufacturing data (i.e., labor required to fabricate the precast slabs) to compute total productivity. However, the scope of most studies is how the use of prefabricated components impacts the production system on site. The use of precast slabs had further positive impacts such as the reduction of concrete waste, and the installation of rebar and embedded electrical conduits in the factory. Furthermore, the surface of the precast slabs does not require further plastering or rework as is required in the traditional system. Thus, the number of downstream activities is reduced. Some additional benefits cannot be quantified but can be qualitatively reported such as increased cleanliness of working areas, less rework, and improved safety.

However, the improvement in productivity and production rate goes hand in hand with design and technical aspects. For example, the initial design of Project B was traditional and was changed during the construction of the basements. This required close coordination between the client, structural designer, site managers, digital teams, and the manufacturer. A 4D simulation was required to assess the new production process and understand the logistics required given the constraints of the site, as shown in Figure 6. This allowed for a detailed planning of the trucks' arrivals, the impact on the neighborhood and the traffic, and the lifting process.

Another aspect that requires further attention is the cultural change to implement off-site components and the buy-in from the client and construction workers. The contractor implemented precast slabs for the first time in Project B. Regarding opportunities for improvement in the implementation of LC in the use of pre-manufactured. In the beginning, there were problems with dispatches due to logistical failures with the factory, problems with transport units, unloading schedules, quality failures in the first pre-slabs, and reduced installation speed, among other factors that were improved with a learning curve and the implementation of the LPS to quickly learn from the mistakes, improve communication with stakeholders and short and medium-term planning to reduce the variability and acknowledge the complexity of the new process to make purposeful changes to make it work. For civil construction work and foremen. They quickly learned the system and with a learning curve, they managed to improve productivity and communication as the levels progressed. They communicated in the weekly meetings that they liked the system and felt the improvement in the system and the savings in rework. In addition, in the beginning, the client was afraid of the joints of the pre-slabs, but when finishing the painting and architecture details, they were convinced of the productive capacity of the system and the good quality of the finishes.

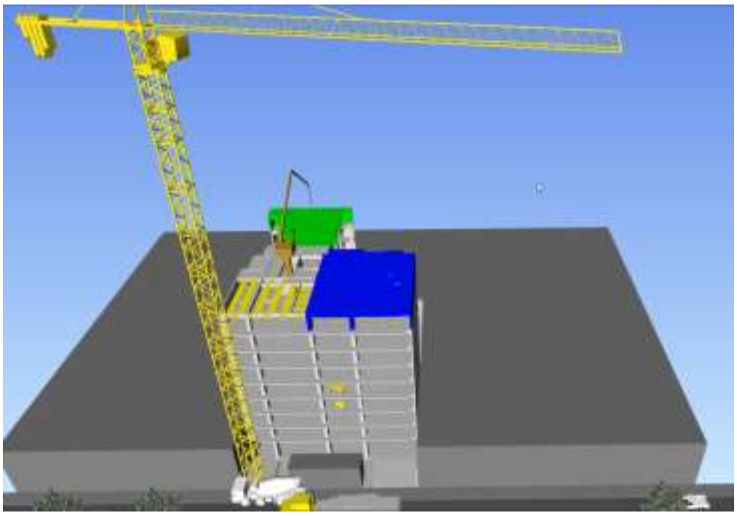

Figure 6**:** A snapshot of a 4D model for improved visualization and constructability analysis

# CONCLUSIONS

The construction sector must continue promoting continuous improvement options to develop residential building projects to reduce the industrialization gap and increase productivity. In this paper, two projects with the same characteristics have been quantitatively analyzed and compared, where it is shown that the use of precast slabs allows an increase in productivity (m2/mh) of 16% compared to the traditional method and an increase of the production rate (m2/day) of 14%. These results would provide practitioners with useful information to decide on the implementation of precast components in construction projects along with the implementation of the LPS needed for appropriate production planning and control. However, the use of precast slabs requires greater look ahead planning of logistics which requires the support of all stakeholders involved in a collaborative environment. The leadership of site managers was pivotal for planning, implementation, and control. Future research could report performance metrics with further precast elements such as columns, shear walls, and beams. It is expected that production rates and onsite productivity would continue to improve. This research can also be extended to the examination of construction flow metrics to provide the evidence-based performance of production flows in industrialized construction (Sacks, 2020).

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