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Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

DEVELOPING A COST-EFFECTIVE, RELIABLE, AND SUSTAINABLE PRECAST SUPPLY SYSTEM UNDER PRICE VOLATILITY AND UNCERTAINTY OF MATERIAL SUPPLY

[LS-23-RP-04]

LSU Proposal ID: AWD-005947, GR-00014941/GR-00014942

Final Report

[November 26, 2024]

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- *Rinker Materials,* Alexandria, LA
- *WASKEY,* Baton Rouge, LA for collaboration and validation of research.

Submitted to:

TRANS-IPIC UTC
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Urbana, IL

Executive Summary

The research project is aimed at developing a cost-effective, reliable, and sustainable precast concrete (PC) supply system under price volatility and uncertainty, divided into three main tasks. The specific research objective of this project was to develop a technique to find optimal ordering and schedule of these materials to deliver to the manufacturing site such that the warehouse can be replenished in a timely fashion to meet the demand and to minimize the flowtime in PC production under various types of uncertainties that include volatile market condition.

Minimizing the total cost of precast concrete production is essential to reducing the overall expenses associated with various transportation infrastructure projects. The total cost for a precast concrete manufacturing company comprises several components, including manufacturing costs, raw material procurement costs, holding costs, and ordering costs. An optimized approach for managing these costs required a thorough understanding of the various factors involved and their interdependencies within the precast concrete production and supply system. For this reason, our research plan was designed to first build a framework to have theoretical insights about the important factors and the direct and indirect relationships among all the factors which was performed (Task 1). From this framework, it is evident that the curing process is a crucial process of production of PC components, specifically which are used in various transportation infrastructures like roads, bridges, and highways. Therefore, minimizing the curing cost will have a greater impact on the minimization of PC manufacturing cost which will also ensure that the production scheduling complies with the delivery deadlines of PC components. This model was developed and run with example data to analyze computational performance (Task 2). On the other hand, the other three enablers of costs, such as holding, material and purchasing costs were addressed in another model, where the demand was considered variable which can change with time and price of the materials also can experience Poisson jumps (Task 3). These three costs mainly depend on the ordering quantity of the materials. Therefore, the mathematical model was formulated by considering the cycle time (inventory cycle) as variable from which the optimal ordering quantity can be determined.

These results will help precast concrete manufacturing companies benefit in the following ways:

- PC companies will benefit from the informed decisions about which raw materials need to be ordered based on demand for PC products and which should be stockpiled in advance for uncertain market and operating conditions based on the inventory cycle, to minimize the total cost including ordering, material purchasing and holding.

- PC companies can better respond to demand fluctuations, reduce costs, and improve operational efficiency, by optimizing their production and inventory strategies, which will ensure that they are well-prepared for any market volatility.

The adoption of these logistic policies will reduce financial waste, ensure material availability for production, and prevent project-delays due to supply shortages, directly contributing to the reliability of transportation infrastructure projects with enhanced effectiveness and economic sustainability.

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A. TRANS-IPIC Final Report

The reliability and sustainability of a cost-effective transportation infrastructure are of prime importance in advancing technologies in precast concrete manufacturing, usage, and transportation supply operations. The price fluctuation of materials and PC (precast concrete) products, and the sustainability of both materials supply and PC structures, are the major factors that dominate the reliability and cost of operating a PC manufacturing system. This research in the *Trans-IPIC/USDOT* project includes how to develop a methodology for a precast supply system that is reliable and sustainable under price volatility and uncertainty in materials supply and delivery.

1. Research Plan - Statement of Problem

The supply channel of the precast process begins with the procurement of raw materials that are processed through the precast concrete (PC) manufacturing operations and subsequently transporting the final products to the point of delivery for assembly or installation on site. This entire process involves different steps that may happen one after another or at the same time, and these processes affect the cost, time, and reliability of the final product or assignment.

***Research Goal**:* Thus, this research aims at developing a cost-effective, sustainable, and reliable supply system considering the presence of price volatility and uncertainty of materials. By understanding these price changes, the study seeks to find the best way to plan the PC supply system to save money and still be reliable and sustainable to deliver the precast products to the transportation construction sites.

2. Research Plan - Summary of Project Activities (Tasks)

The costs, sustainability, and reliability of the PC systems and components related to the transportation are the three main ingredients that need to be addressed in this research. The one-year (2024) research undertaken includes:

- **Task 1:** A *Structural Self-Interaction matrix* to be developed to extract different controlling variables and system parameters or factors that affect the stated performance outcome of the PC supply system, and the reliability and manufacturing cost of precast concretes.
- **Task 2:** A cost-reliability-sustainability (CRS) model will be formulated to minimize the expected cost of production and supply system of PC and simultaneously improve the reliability and sustainability of the system.
- **Task 3:** UPV (*Uncertainty and Price Volatility*): Process variability and expected cost with individual material's prices and supply uncertainty will be considered for refurbishing the warehouse in time.

3. Life Cycle of project

The inception of the project began with identifying critical challenges within the precast concrete (PC) supply and production chain, especially focusing on transportation infrastructure projects. The needs of key industry such as cost reduction, efficient ordering policy, demand forecasting under uncertainty, and sustainability were highlighted primarily from the suppliers' perspectives. Initial discussions with industry partners such as WASKEY, Premier Concrete Products, and Gainey's provided valuable insights into real-world issues, forming the basis for specific tasks that would be undertaken. The research was then divided into three main tasks:

Task 1: A well-constructed structural self-interaction matrix can help identify key controlling variables and system parameters or factors influencing the performance of the precast concrete supply system, particularly in terms of reliability and manufacturing cost. Therefore, the first task focused on developing a hierarchical framework (Figure 1) to illustrate the interrelationships among factors in the precast concrete (PC) production and supply systems. The diagram in Figure 2 is constructed using the *Interpretive Structural Modelling (ISM)* approach, where the factors are organized according to their levels and illustrating their interactions.

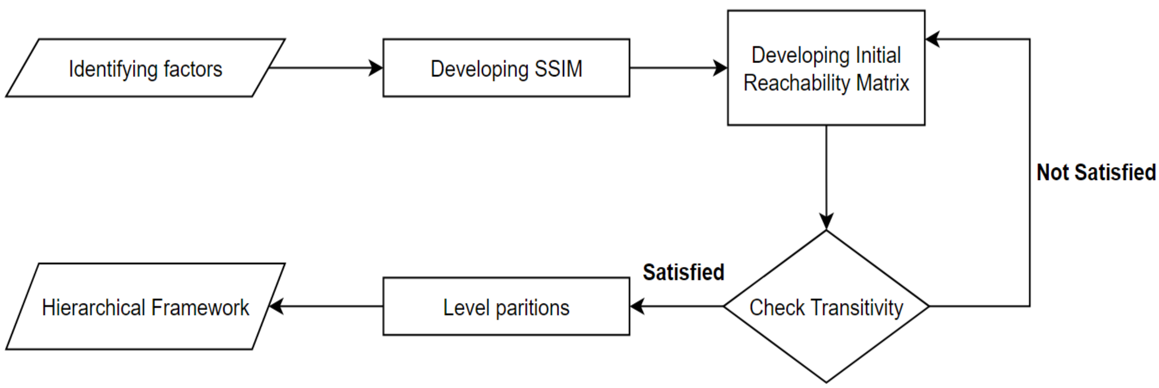

Figure 1. Methodology of constructing the hierarchical framework of factors

For instance, a specific algorithm was used to transform the structural self-interaction matrix into a reachability matrix, providing a more accurate numerical representation of interdependencies. Assume S as the Structural Self-Interaction Matrix (SSIM) and R as Reachability Matrix. Both matrices have i rows and j columns. Therefore, $S = [s_{ij}]$ and $R = [r_{ij}]$. The SSIM format then was converted to reachability matrix by using following rules:

- If s_{ij} = Forward relation, then r_{ij}= 1 and r_{ji} = 0
- If s_{ij} = Reverse relation, then r_{ij} = 0 and r_{ji} = 1
- If s_{ij} = Both ways, then r_{ij} = r_{ji} = 1
- If s_{ij} = 0 or no relation, then r_{ij} = r_{ji}= 0

Subsequently, level partitions were conducted using the reachability matrix to group the factors based on their significance. Once all factors were assigned to their respective levels, the factors were connected to the other related factors with solid or dashed lines.

The obtained framework categorized and depicted the dependencies among key factors such as cost, reliability, and sustainability, to assess their combined impact on the durability of transportation infrastructure. Dashed lines denote transitive relationships among the factors, while solid arrows indicate direct links. A factor positioned at an elevated level signifies its capacity to impact many other factors (Yadav and Samuel, 2022). This visual representation serves as a map, outlining the hierarchical organization and the intricate web of interconnections between various elements within the system. By clearly illustrating how different factors relate and interact with one another, the diagram becomes an invaluable tool in the system's analysis phase.

Using the ISM approach to develop a hierarchical framework in precast concrete production and supply chain is essential for enhancing the durability of transportation infrastructure. ISM helps clarify how different factors such as material quality, manufacturing processes, and logistics interact and influence each other. This understanding allows decision-makers to focus on the most critical aspects, leading to smarter resource allocation and improved strategic planning. By identifying potential risks and how they impact each other, companies can proactively address problems before they compromise the final product. Furthermore, a clear model of interdependencies fosters innovation and process improvements specifically where they will enhance the durability and performance of precast concrete in infrastructure projects.

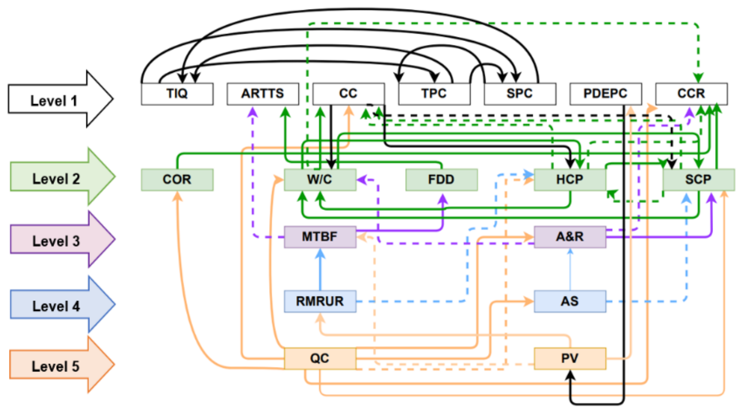

Figure 2. Diagram representing the dependence relationships of the Factors

Task 2: In addressing the objective of developing a comprehensive cost-reliability and sustainability model for the precast concrete supply system, it became evident that curing costs play a critical role in determining the overall efficiency and effectiveness of the process. To align with the objectives of minimizing costs, ensuring product reliability, and promoting sustainable practices, the team worked on minimizing the curing costs, a significant component of PC production expenses.

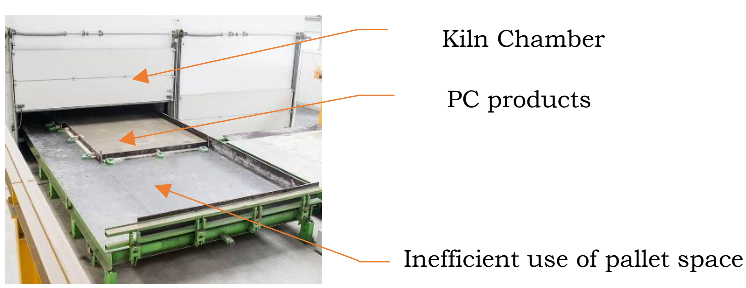

Figure 3. Mold placement on a pallet in curing process

A Curing Cost Minimization (CCM) model was developed to optimize pallet space utilization in curing chambers (Figure 3), aiming to reduce energy and labor costs while meeting strict project deadlines. This model incorporated constraints like component dimensions and delivery schedules, testing the impact of different demand levels and component sizes on curing costs and computational performance. Initial results showed that increasing demand and component size slightly raised costs but reduced batch sizes and pallet numbers, leading to cost savings. The developed CCM model was applied to maximize pallet capacity while minimizing energy and labor expenses.

Thus, by analyzing the curing process with different system's parameters, the CCM problem can be formulated as an integer non-linear programming (INLP) problem to find the minimum number of pallets with multiple pc component (i) of various concrete mixtures (k), x_{jk} ($j = 1, 2, \ldots, n$; $k=1,2, \ldots, p$) with maximum value of PC components per layout (j), a_{ij} to minimize the total curing cost.

CCM: $$Min\ Z_c = \sum_{k=1}^{p}(Ec_E T_k N_b + c_L t_L N_{c_k}) \quad (1)$$

$$\sum_{i=1}^{m} L_i W_i\, a_{ij} \leq LW, \qquad \forall j = 1, \ldots, n \quad (1a)$$

$$\sum_{k=1}^{p}\sum_{j=1}^{n} a_{ij}\, x_{jk} \geq D_i, \qquad \forall j = 1, \ldots, n \quad (1b)$$

$$\sum_{k=1}^{p}\sum_{j=1}^{n} a_{ij}\, x_{jk} T_k \leq d_i, \qquad \forall i = 1, \ldots, m \quad (1c)$$

$$a_{ij}, x_{jk} \geq 0 \text{ and integers} \qquad \forall i = 1, \ldots, m; j = 1, \ldots, n \quad (1d)$$

This model incorporates various technical constraints, such as component dimensions and delivery deadlines, to determine the optimal number of pallets and configurations required for efficient and cost-effective operations. These findings suggest that the model not only enhances production efficiency but also promotes sustainability, ensuring that PC components meet the required quality standards while supporting the development of durable and economical transportation infrastructure projects.

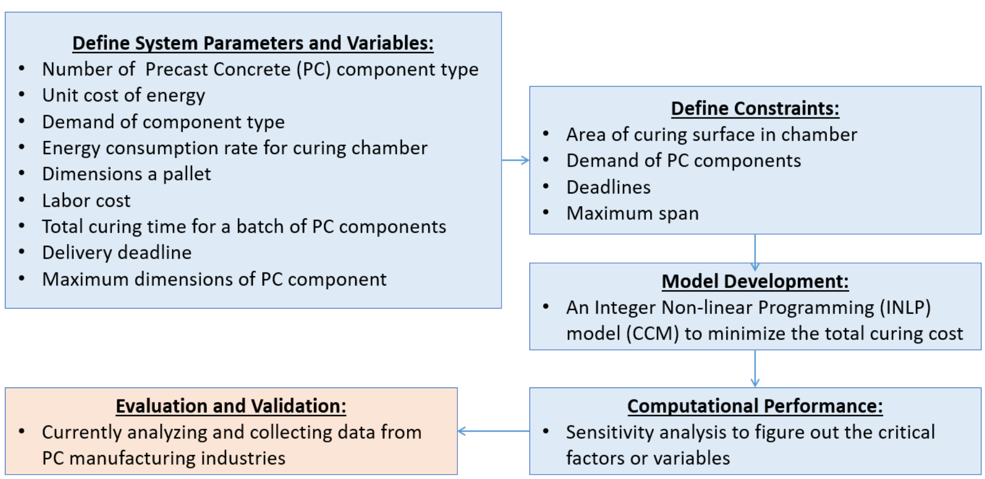

Figure 4. Development of Curing Cost Minimization Model

For the evaluation and validation phase of the CCM model (Figure 4), several random values were assigned to some variables such as dimensions of PC components, demand for those PC products and dimensions of the surface of curing chamber. From the research perspective, the computational performance (Table 1) results were analyzed and found out the following points:

Table 1. Computational results for randomly generated data with input and output data

Problem #		Variables	Input Data	Optimal Solutions			
				$[(\boldsymbol{a_{11}}, \boldsymbol{a_{21}}, \boldsymbol{a_{31}})^T, (\boldsymbol{a_{12}}, \boldsymbol{a_{22}}, \boldsymbol{a_{32}},)^T]$	(x_1, x_2)	Z_c (\$)	CPU†(sec)
1	(a)	D_i	$[8 \quad 11 \quad 6]^T$	$[(1,2,1)^T, \quad (3,1,1)^T]$	(5,1)	651.20	22.79
	(b)	D_i	$[10 \quad 14 \quad 4]^T$	$[(3,3,0)^T, \quad (1,2,1)^T]$	(2,4)	711.20	58.43
	(c)	D_i	$[15 \quad 8 \quad 6]^T$	$[(0,3,1)^T, \quad (3,1,1)^T]$	(1,5)	731.20	45.06
2	(a)	L_i, W_i	$([10 \quad 8 \quad 15]^T, [8 \quad 4 \quad 6]^T)$	$[(3,4,1)^T, \quad (1,0,2)^T]$	(3,1)	640.80	20.95
	(b)	L_i, W_i	$([14 \quad 12 \quad 16]^T, [12 \quad 10 \quad 8]^T)$	$[(0,2,0)^T, \quad (2,2,1)^T]$	(1,5)	691.20	29.51
3	(a)	L, W	(30,25)	$[(0,2,0)^T, \quad (2,2,1)^T]$	(1,5)	691.2	4.73
	(b)	L, W	(35,30)	$[(3,4,2)^T, \quad (2,3,2)^T]$	(2,1)	575.6	6.25
	(c)	L, W	(65,60)	$[(1,4,4)^T, \quad (7,7,2)^T]$	(1,1)	550.4	5.99

† CPU time on *11th Gen Intel(R) Core (TM) i7-11700 CPU @ 2.50 GHz processor* and 16 GB installed RAM

- When the demand per PC component increases, the curing cost as well as the computational time also increases.
- When the length and width of PC component increases, the curing cost and CPU time also increase but at comparatively lower rate.
- If more components are assigned on the pallet of the curing chamber, fewer pallets are needed and so are the batch sizes leading to less cost.

We are currently collaborating with WASKEY and Gainey's to collect data and critical information to adapt and refine our model for real-world applications.

Task 3: The third task addressed demand uncertainty and price volatility, developing a mathematical model to find the optimal ordering quantities of multiple raw materials and cycle lengths for multi-period inventory systems with fluctuating demands for PC components and uncertain price jumps of raw materials. This model introduced the average total inventory cost incurred in each cycle with the following assumptions:

- The inventory contains multiple raw materials for manufacturing several PC products.
- The instantaneous replenishment of the inventory materials (that is, the lead time is zero for any order).
- A continuous review policy is applied (that is, the current inventory level of any item is known at any point in time).
- Demand increases or decreases exponentially, and price varies jump with Poisson distribution
- No shortage is allowed.

In the production cycle of multiple precast concrete products, a challenge arises in determining optimal ordering policy of raw materials for manufacturing various precast concrete components while managing the supply chain efficiently. The process requires a variety of raw materials, each needed in different quantities depending on the specific PC product being manufactured. As the precast concrete products are diverse, the raw material requirements for each product vary, making it necessary to coordinate the ordering and usage of multiple raw materials

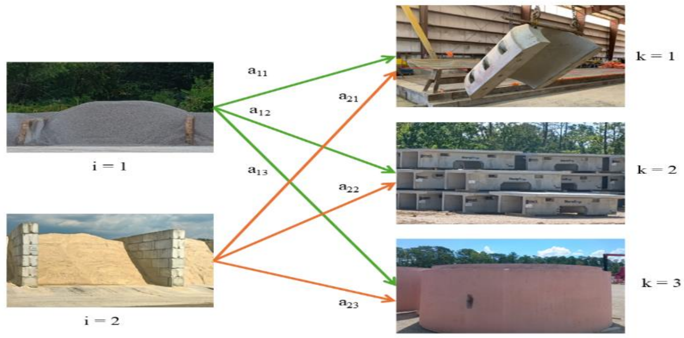

Figure 5. Different raw material requirements for production of multiple PC components

effectively.

For example, in Figure 5, a_{ik} is the required amount of raw material types i (e.g., cement, fly ash and other cementitious compounds) to manufacture different types of PC products k (e.g., arch bridges, bridge girders, box culverts as shown in Figure 6) in kg/unit. A significant complication emerges from the fact that the demand, $D_k(t)$ for various precast concrete products, fluctuates over time, rather than remains constant. In the examination of a multi-period supply chain system of multiple raw materials with linearly increasing demand for PC manufacturing industries, in which demand for multiple raw materials increases linearly with time, *i.e.,* $D_k(t) = D_{k_o} + \beta_k t$, where the demand growth rate $\beta_k > 0$. Here, shortage is not allowed; therefore the ordering quantity of the j-th cycle for material i, Q_{ij} $(j = 1,2,3,\dots,J)$ will increase from one cycle to another to satisfy the increasing demand of precast products $\sum_{k=1}^{K} a_{ik} D_k(t)$, because different amount of multiple raw materials will be utilized to manufacture several PC products.

Figure 6. Different PC components used in Transportation Infrastructures

This variability in demand introduces uncertainty, which complicates the decision-making process for batch sizing and raw material procurement. If materials are procured too early or in excess, it leads to high storage costs and the risk of materials degrading over time. Conversely, delays in production can disrupt the entire construction schedule, causing costly delays and penalties. In addition to the demand uncertainty, the prices of the raw materials used to manufacture these products are also subject to change. Price of a material i, $c_i(t)$ can be evolved according to a Poisson process for the growth rate. If the growth rate λ_i for the cost of material i jumps according to a Poisson distribution given by

$$\boldsymbol{P}[N_i(t) = x] = \frac{(\lambda_i t)^x e^{-\lambda_i t}}{x!} \quad (2)$$

where $N_i(t)$ represents the number of jumps in the cost growth over time t, and λ_i is the rate at which the jumps occur (Kardar, 2007). Each jump (Figure 7) represents a sudden increase in the material cost. After each jump, the cost increases by a

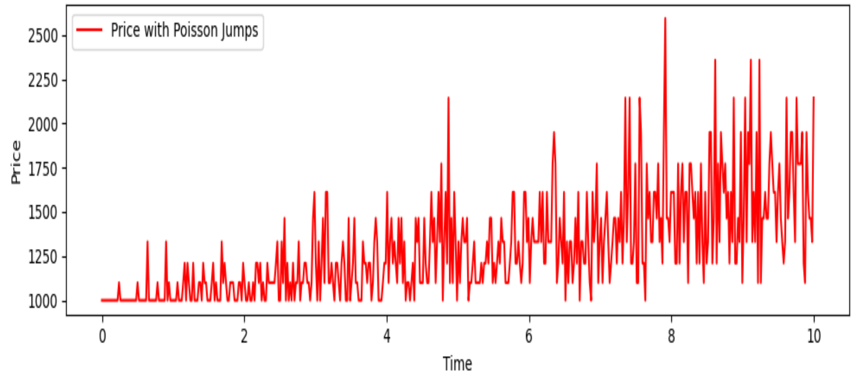

Figure 7. Price of raw materials with Poisson Distribution

factor of α_i, where $\alpha_i > 1$ represents the magnitude of the price jump. Thus, the material cost at time t, given $N_i(t)$ jumps, is given by $c_i(t) = c_{i_o}{\alpha_i}^{N_i(t)}$; where c_{i_o} is the initial cost.

These price fluctuations make it difficult to anticipate costs and plan the timing of material orders, which adds another layer of complexity to the supply chain management. Under consideration of such variable demand scenarios and uncertain price jumps, a mathematical model was developed to calculate the average total inventory cost (including fixed ordering cost A, material purchasing cost P) incurred in the jth cycle TC_j ($j = 1,2,3, \ldots, J$), which is a convex function with respect to the variable T_j where $T_j > 0$. The function is given below:

$$TC_j = \frac{1}{T_j}\left[A + P + HT_j\overline{I_{ij}}\,\right]$$

$$= \left[\frac{A}{T_j} + \sum_{k=1}^{K} \frac{a_{ik}c_{i_o}c_i(t_j)}{\lambda_i(\alpha_i - 1)c_i(t_{j-1})}\left[\frac{D_{k_o}}{T_j} + \beta_k - \frac{\beta_k}{\lambda_i(\alpha_i - 1)T_j}\right] + H\sum_{k=1}^{K} a_{ik}\left[\frac{\beta_k}{3}{T_j}^2 + \frac{D_k(t_{j-1})}{2}T_j\right]\right] \quad \forall i \qquad (3)$$

Therefore, $\frac{\partial TC_j}{\partial T_j} = 0$ has led to the following equation

$$-A + \sum_{k=1}^{K} a_{ik}\left[\frac{c_{i_o}c_i(t_j)D_{k_o}}{\lambda_i(\alpha_i - 1)c_i(t_{j-1})} + \frac{\beta_k}{\lambda_i(\alpha_i - 1)} + \frac{2H\beta_k}{3}{T_j}^3 + \frac{D_k(t_{j-1})}{2}{T_j}^2\right] = 0 \quad \forall i. \qquad (4)$$

As this equation (4) is a cubic function in T_j, it certainly has one real solution. As periodic review policy is considered for this problem, $T_j = t_j - t_{j-1}, t_0 = 0$ for $j = 1,2,3, \ldots, J$. Therefore, $t_j = T_1 + T_2 + T_3 + \cdots + T_j$ for $j = 1,2,3, \ldots, J$. This is due to the fact that the quantity ordered for multiple materials at the beginning of each cycle is consumed up at the end of that cycle. Here, t_j is the ending point of jth cycle and the beginning point of $(j + 1)$th cycle on a timeline. To analyze the computational performance of this model, this optimal ordering policy was applied to solve an illustrative case study for single raw material ($i = 1$) and two types of PC products ($k = 2$) and for a case study problem.

The behavior of the demand rate over the two different phases (increasing and decreasing) is shown graphically in Figure 8. Also, in Table 2, the ordering quantities Q_{ij}^* decreases when the demand decreases but the cycle length (the time of the cyclic consumption) becomes longer, unlike the situation with the increasing demand (from cycle 1 to cycle 5 in Table 2).

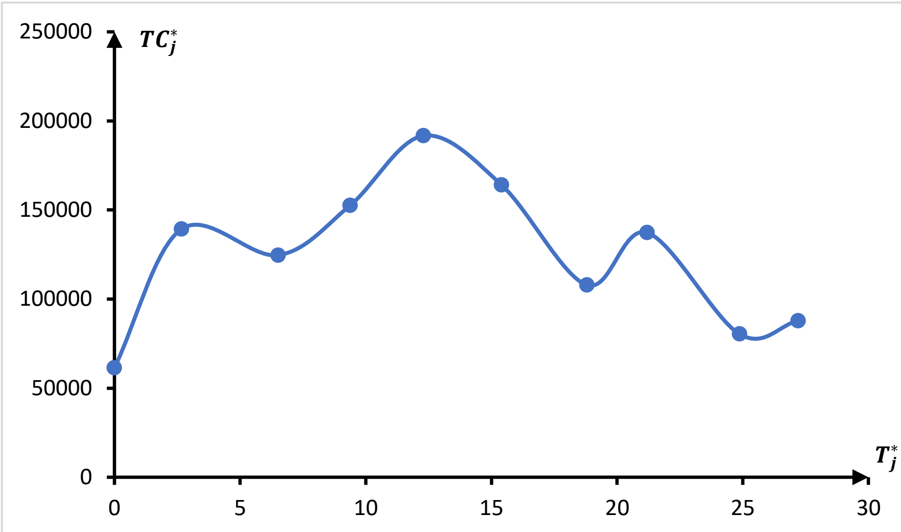

Figure 8. Behavior of total cost with time

Table 2. Sub-optimal policies for increasing and decreasing demand pattern

Cycle I	t_{j-1}^* (months)	$D_1(t_{j-1}^*)$ (units)	$D_2(t_{j-1}^*)$ (units)	T_j^* (months)	Q_{ij}^* (units)	TC_j^* ($)
1	0	20	12	2.67	61,423	178,356
2	2.67	31.52	19.68	3.84	139,315	201,599
3	6.51	40.13	25.42	2.87	124,658	190,258
4	9.38	48.89	32.26	2.92	152,628	225,894
5	12.30	58.16	37.44	3.10	191,704	248,652
6	15.40	51.39	34.06	3.40	164,101	215,983
7	18.80	46.59	31.66	2.40	107,856	185,649
8	21.20	39.25	27.99	3.67	137,281	199,685
9	24.87	34.59	25.66	2.33	80,388	180,564
10	27.20	28.41	22.57	3.09	87,845	188,953

By analyzing the computational performance of this model, the following characteristics can be identified:

(a) When the demand is increasing, the on-hand inventory is proportional to the demand for PC products at certain point of time t.
(b) The material purchasing cost (P) is proportional to the ratio of the current unit cost of material i to the unit cost at the preceding time point (when the cost is evolving through the Poisson price jumps).

Therefore, this ordering policy tailored to precast concrete manufacturing companies will enable them to navigate challenging market conditions. By using this policy,

- the companies will be helped make informed decisions about which raw materials (i) need to be ordered based on demand for particular PC products (k) and which should be stockpiled in advance for uncertain market and operating conditions based on the inventory cycle (j) to minimize the total cost including ordering (A), material purchasing (P) and holding (H).
- Companies can better respond to demand fluctuations, reduce costs, and improve operational efficiency, by optimizing their production and inventory strategies, which will ensure that they are well-prepared for any market volatility.

Future Research Plans:

- Continuous review policy of inventory of precast raw materials will be considered for better performance of the precast manufacturing companies.
- Multiple demand distributions as they may prevail in different situations with different inventory items will be applied to reflect the actual situation, and cases regarding supply disruptions can also be considered.

B. RESEARCH CONTRIBUTION

4. Educational outreach

(a) A 13-member meeting of 4 companies and LTRC was held at Louisiana Concrete Association (LCA) on August 14, 2024, to discuss the possible collaboration with Trans-IPIC and the PI has already interacted with Louisiana Concrete Association (LCA), American Concrete Pipe Association (ACPA), WASKEY, Premier Concrete Products (PCP), Gainey's Concrete Products (GCP), and Rinker Materials for corrective feedback on the project.

(b) A total of 12 students have been assigned to the following research projects in their respective industries as part of the coursework for IE-4597 Senior Design Project I (Fall 2024). These projects have been selected based on mutual interests of the precast concrete manufacturers' need and Trans-IPIC research agenda. These projects are identified based on their potential impact on the precast concrete manufacturing for transportation infrastructure. Though they may not seem related directly to the transportation, yet they contribute significantly to the highway and bridge construction directly and/or indirectly in reducing the manpower cost, travel distance and transport time, waiting time, and managing the project schedule more effectively. For example, Tracking and storage of machine parts for PC production machines, optimizing the PC pickup truck flow, resource allocation for PC shipping, and dunnage design for minimizing damages in transporting the PC products are some typical problems faced by PC manufacturers. The projects currently undertaken by senior capstan design are listed below:

1. Tracking and storing Besser machines parts for precast concrete manufacturing at Premier Concrete Products, Denham Spring, LA
2. Optimizing the yard layout to improve truck flow in transporting precast materials inventory at Premier Concrete Products, Denham Spring, LA
3. Improving Yard Layout for Efficient Handling and Tracking of Precast Concrete Products at WASKEY, Baton Rouge, LA

4. Design of dunnage and rigging for oversized PC: Ensuring stability & minimizing damages at Gainey's Concrete, Holden, LA

Sustainment of such an effective approach for addressing the manufacturing problems at the onset of the precast transportation system will help maintain a long-lasting, cost-effective transportation system. The results obtained from stated senior design projects currently undertaken will be used to extended them into the second cycle of the Trans-IPIC research project to further enhance the findings.

5. Workforce development

(a) The team is in contact with LTRC (Louisiana Transportation Research Center) representative (Dr. Tyson Rupnow, Director) to assist and advise on the project.

(b) Precast concrete plants visited/meeting (Summary):

- Louisiana Transportation Research Center Meeting (June 11, 2024)
- Louisiana Concrete Assoc. Tech. Committee Meeting (August 14, 2024)
- WASKEY, Baton Rouge, LA (August 14, 2024)
- Premier Concrete Products, Denham Spring, LA (August 12 & 14, 2024)
- Gainey's Concrete Products, Holden, LA (August 26, 2024)
- Rinker Materials Workshop, Alexandria, LA (September 23, 2024)
- Concrete Pipe Seminar at Louisiana Concrete Assoc. office (to be held on December 4, 2024)

The purpose of visiting these companies was to gain first-hand knowledge on the problem the concrete companies are currently facing in meeting the systems specifications and customer demands in transportation infrastructure.

6. Technology Transfer

The research team is in contact with several companies through LTRC. Efforts have been made to collaborate and collect some real-life data for testing purposes and feedback on the project. The outcome is yet to be achieved for technology transfer.

7. Papers that include TRANS-IPIC UTC in the acknowledgments section:

1. Mazumder, A. and Sarker, B. R. (2024a), "Developing an interpretive structural model for factors affecting cost effectiveness, reliability and sustainability of precast concrete," *Working Paper* #1 (outcome of QPR-1, January 1 - March 31, 2024).

2. Mazumder, A. and Sarker, B. R. (2024b), "Optimizing Pallet Capacity Utilization to Minimize Curing Cost in Precast Concrete Manufacturing," *Working Pape*r #2 (Outcome of QPR-2, April 1 - June 30, 2024).

3. Mazumder, A. and Sarker, B. R. (2024c), "Optimizing Raw Material Ordering Policies for Efficient Precast Concrete Production under Fluctuating Demand and Price," *Working Pape*r #3 (Outcome of QPR-3, April 1 - June 30, 2024) (Abstract submitted in IISE Annual Conference & Expo 2025).

8. Presentations and Posters of TRANS-IPIC funded research:

1. Mazumder, A. and Sarker, B. R., "Factors of the Precast Concrete Supply Chain: An Interpretive Structural Modeling Approach," *Graduate Research Conference (GRC)*,

presented at the Students' Union, Louisiana State University, Baton Rouge, LA on April 30, 2024.

2. Mazumder, A., and Sarker, B.R., "Exploring Interdependencies of Factors in Precast Concrete Supply System: An Interpretive Structural Modeling Approach," presented at the *DOT TRANS-IPIC Workshop* (Grant #LS-23-RP-04), Big Ten Conference Center, 5440 Park Place, Rosemont, IL, April 22, 2024.

3. Mazumder, A. and Sarker, B. R. (2024c), "Optimizing Raw Material Ordering Policies for Efficient Precast Concrete Production under Fluctuating Demand and Price," *Working Paper* #3 (Outcome of QPR-3, April 1 - June 30, 2024) (Abstract submitted for Presenting in IISE Annual Conference & Expo 2025).

9. Please list any other events or activities that highlights the work of TRANS-IPIC occurring at the university:

1. Mazumder, A. and Sarker, B. R., "Factors of the Precast Concrete Supply Chain: An Interpretive Structural Modeling Approach," Graduate Research Conference (GRC), presented at the Students' Union, Louisiana State University, Baton Rouge, LA on April 30, 2024.

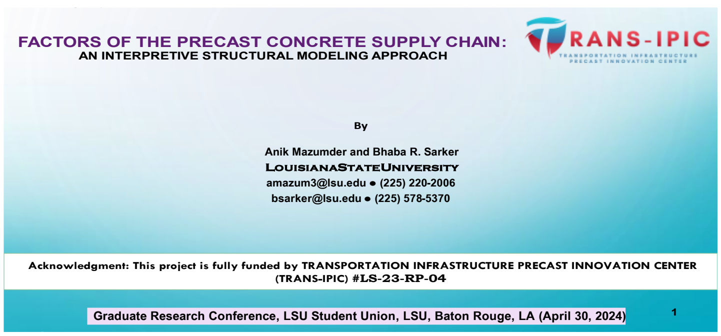

Figure 9. Cover Slide of the presentation file that was presented at GRC, LSU.

2. Mazumder, A. and Sarker, B. R., "Optimizing Pallet Capacity Utilization to Minimize Curing Cost in Precast Concrete Manufacturing," presented at the *DOT TRANS-IPIC* online research online seminar on July 22, 2024.
3. Plant Tour at Rinker Materials, Alexandria, LA on September 23, 2024 (2.0 Professional Development Hours)

Figure 10. Research online seminar presentation on July 22, 2024

Figure 11. Certificate of attendance from Rinker Materials

10. List of any references to TRANS-IPIC in the news or interviews from the research:

(a) The team has referred **TRANS-IPIC** in the meeting with LTRC (Louisiana Transportation Research Center) representative (Dr. Tyson Rupnow, Director) for asking his assistance and advice on the project.

(b) A 13-member meeting of 4 companies and LTRC was held at Louisiana Concrete Association (LCA) on August 14, 2024, to discuss the possible collaboration with **Trans-IPIC** and the PI has already interacted with WASKEY, Premier Concrete Products (PPP), Gainey's Concrete Products (GCP), and Rinker Materials for corrective feedback on the project.

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11. Mazumder, A. and Sarker, B. R. (2024b), "Optimizing Pallet Capacity Utilization to Minimize Curing Cost in Precast Concrete Manufacturing," *Working Paper #2* (Outcome of QPR-2, April 1 - June 30, 2024).
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