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Scope: The Journal of Management and Engineering Integration (JMEI) is a double-blind refereed journal dedicated to exploring the nexus of management and engineering issues of the day. JMEI publishes two issues per year, one in the Summer and another in Winter. The Journal's scope is to provide a forum where engineering and management professionals can share and exchange their ideas for the collaboration and integration of Management and Engineering research and publications. The journal will aim on targeting publications and research that emphasizes the integrative nature of business, management, computers and engineering within a global context.

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The Journal Editorial Team would like to thank the reviewers for their time and effort. The comments that we received were very constructive and detailed. They have been very helpful in our effort to continue to produce a top-quality journal. Your participation and timely response are very important for providing a distinguished outlet for original articles. In this issue, articles are assigned digital object identification (DOI) numbers to make sure readers and researchers can reliably find your work and to help track the ways your work is cited by others.

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Abstract

Lean has been around for many years, and many companies have benefited from the principles embodied within it. With the emergence of smart factories and ever-increasing connectedness, many opportunities exist to regain the competitive advantage once sought in the basic principles of lean. Artificial intelligence is a broad and widely used term. Within artificial intelligence, subsets of techniques can be used to drive decision-making. One method is clustering. Clustering algorithms group data without specified labels. One potential application for clustering with respect to lean is to evaluate data from organizations to develop clusters of companies that have successfully implemented lean and those that have not, along with critical success factors that align with these clusters. A survey was distributed via social networking to industry professionals to gather data on factors influencing lean implementation. The survey data was utilized to perform clustering analysis and understand the factors that need to be evaluated to determine a company's lean culture. A random forest algorithm (missForest) was utilized as an imputation method for missing data prior to performing k-modes clustering. Three clusters were identified with mode values representing a low, medium, and high degree of lean implementation within an organization. Additionally, several other factors that followed this same convention were identified. These results lend themselves towards the idea that a follow-on supervised algorithm could be implemented using this data as a training set to monitor organizations and help them focus on the areas needed to implement lean successfully.

Keywords: *Lean; Random Forest; Artificial Intelligence; Cluster Analysis*

1. Introduction

The term lean has become ingrained into the modern business world. Since manufacturing companies started to adopt the Toyota Production System (TPS) worldwide in the 1980s, lean has transformed from a buzzword for American manufacturing companies into a philosophy that permeates all areas of business worldwide. Lean has become so ingrained in many businesses that

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it is no longer referred to as lean or TPS. Today, many businesses have built their own identity around these principles that have become foundational. They have rebranded them to reflect the organization's deep-seated belief in the fundamental truth that spurred the lean revolution. These principles work. Examples are Lockheed Martin's LM21, Boeing's Boeing Production System, and Volvo's Volvo Production System. The principles of waste elimination, continuous improvement, and visual controls, amongst many other principles, are seen throughout organizations and industries and often never referred to as lean. It is no longer just something different that organizations do to create an advantage; often, it is a standard that organizations must compete at a basic level. Even so, many companies fail to implement lean successfully, only see limited benefits, and never realize the full potential, or fail to identify opportunities outside traditional manufacturing applications.

The first three industrial revolutions brought considerable change and advancement throughout the world, and the fourth industrial revolution is poised to do the same. What seemed like science fiction not long ago is becoming reality today. Industry 4.0, the internet of things (IoT), internet of systems (IoS), smart technology, and artificial intelligence (AI) are all connected to and a part of the new industrial revolution. As organizations have begun connecting systems and equipment in new ways, new data streams and ways to view organizational health have been produced. From a manufacturing perspective, large amounts of machine and process data can be collected inexpensively and used to improve processes and performance continuously. This drives the top-tier performance that initially spurred the widespread adoption of lean. Industry 4.0 could usher in a new era of continuous improvement that relies heavily on dynamic, real-time data to provide feedback and continuous course correction to keep machines, processes, people, company, and profits headed in the right direction.

In the era of big data and AI, companies can make accurate, real-time predictions to improve their operations. Clustering algorithms are used in areas such as image processing, financial analysis, genetics, social networks, and even to recommend what shows you might be interested in watching on streaming services such as Netflix and Hulu (Nagy, 2018). The algorithms can quickly partition the data and find clusters and trends. Xu and Wunsch (2008) describe clustering as an unsupervised classification system that aims to partition unlabeled datasets into a finite and discrete set of "hidden" and natural data structures. Essentially, the algorithms explore the dataset and identify patterns or structures in the data that may otherwise be nearly impossible to find. Further, Sathya and Abraham (2013) describe supervised learning algorithms as needing a teacher or supervisor to train examples of classes. Therefore, if one could utilize clustering to identify the data structures around successful and unsuccessful implementation, a supervised learning technique could be implemented to classify data into one of these structures continuously.

Several studies have determined different clustering methods to increase manufacturing efficiencies or lean implementation. For example, Qattawi and Madathil (2019) utilized clustering to identify commonality between assembly tasks for different engine models to decrease tooling, station setup, and changeover. Antunes and Poshdar (2018) sought to describe a facility rooted in machine learning that constantly captures images from within the facility to monitor and automatically generate material requests and inventory replenishments, among other operations. Fuzzy-C-Mediods clustering was proposed by Padayachee & Bright (2017) as a method to cluster manufacturing part families to improve manufacturing cell efficiency. Additionally, Chen et al. (2019), Cheng et al. (2019), Manns & Deuse (2015), Huang et al. (2010), and PengjiaWang et al. (2014) proposed different approaches to utilizing clustering methods to increase manufacturing efficiency.

There have also been similar attempts to utilize clustering analysis as part of an approach to assess lean implementation. Marodin et al. (2016) utilized a survey of 64 Brazilian automotive manufacturing firms to gather information on lean implementation. The research utilized a hierarchical algorithm to identify the number of potential clusters. Then, a k-means clustering approach was employed to allow for the discrimination of the original clusters obtained. Netland and Ferdows (2016) utilized a hierarchical and furthest neighbor clustering method as one step in a multiple-step process to cluster Volvo plants worldwide based on levels of lean implementation.

One of the immediate applications that could be utilized at the confluence of these ideas is lean implementation. As mentioned previously, many companies often fail to implement lean in a meaningful way successfully. If organizations could understand the factors that drive a successful lean implementation and monitor their organizational systems, they could constantly classify teams, divisions, or entire business units into a defined readiness level. Along with a readiness level, organizations could also determine focus areas to help drive improvement in the areas deemed lacking for a successful implementation. This paper proposes a methodology to accomplish the first step in that proposal by utilizing cluster analysis to identify influential factors in successful lean implementation. If clusters that align with successful and unsuccessful implementation of lean can be identified, a supervised learning technique can be developed to aid organizations in successfully implementing lean.

The goal of this research is to utilize clustering algorithms to identify those factors that are important for lean implementation. These factors and data could then be used as a training set for a supervised algorithm to aid organizations in implementing lean.

2. Research Methodology

This research aims to propose a technique that can be used to analyze survey data and identify the factors that are influential in the successful implementation of lean in organizations. The research methodology included survey distribution and collection, pre-cleaning of the data, and implementation of the k-modes clustering algorithm in R. Further, the results of the clustering algorithm will be discussed along with an analysis of the implications. Additionally, regression analysis was performed on the same data set and compared to the cluster analysis results.

The data used in this work was obtained through a survey distributed on LinkedIn to industry professionals. Before distributing the survey, Institutional Review Board (IRB) approval was secured. A total of 196 responses were obtained, covering 52 questions. Initial data cleaning was performed to eliminate any responses that were missing for more than 50% of the questions. This removed 51 responses from the dataset. For these 51 responses, the respondents started filling out the survey, answered a small portion of the initial demographic questions, and exited the survey. There were no responses to any of the questions concerning lean and were removed from the data set.

Many of the questions were based on a five-point Likert scale; however, some were not. Some questions provided the respondent with more options to choose from. For example, the respondents were asked to identify the region in which they live and were provided with six options. Respondents were also asked to identify the industry in which they work and were provided with 42 options. All the responses were transformed into numeric factors to simplify the analysis. In the previous two example questions, the six regions were transformed into numeric factors, one through six. Similarly, the industry responses were transformed into numeric factors, one through 42. All responses to all questions were categorical.

The goal of this survey was to capture a diverse, global sample. Figure 1 summarizes the number of respondents by region. While representation was from many different regions, North America was the most heavily represented, and Europe the second most represented. Beyond North America and Europe, the representation of other regions was sparse.

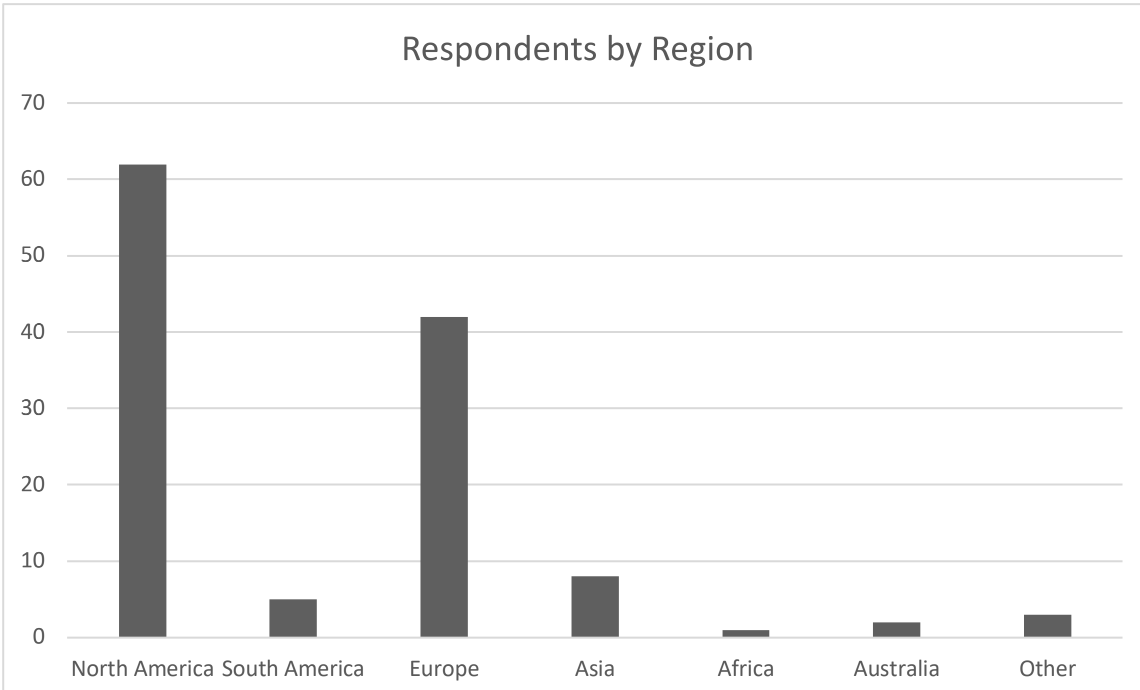

Figure 1. Survey Respondents by Region

Respondents were also asked to provide their years of work experience. Figure 2 provides the work experience of the survey respondents. The most represented group falls into the “more than 20 years” of experience group. However, there was also a strong representation of responses from mid-career and early-career professionals.

In addition to their general work experience, respondents were also asked to provide details on their lean experience. Figure 3 details the lean experience of the survey respondents. As indicated, there is a broad mix of experience from a few months to over fifteen years. This mix of lean experience should help provide a more thorough view on the survey questions, instead of having all respondents with minimal experience or 15+ years of experience.

After the initial cleaning and transformation of the data into numeric factors, many responses were still missing some data. In total, 516 data points (6.8% of the total dataset) were missing. An imputation method based on the random forest (RF) algorithm was selected to address the missing data. Stekhoven and Buhlmann (2011) proposed an RF method (missForest) for imputing missing data onto data sets containing mixed data types. The method needs no tuning parameter and requires no prior knowledge of the data. Additionally, the method has been shown to outperform many other common methods for imputing categorical data and is a readily available package in R.

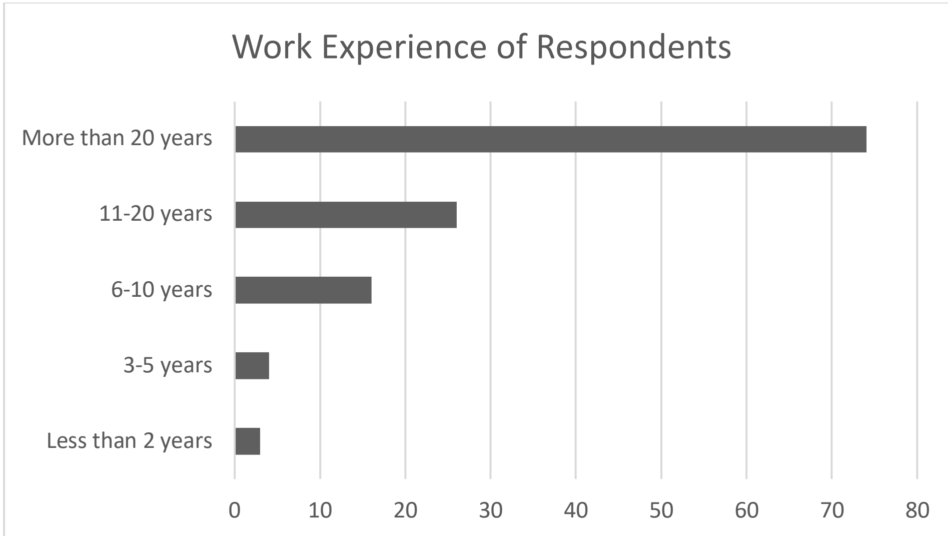

Figure 2. Work Experience of Survey Respondents

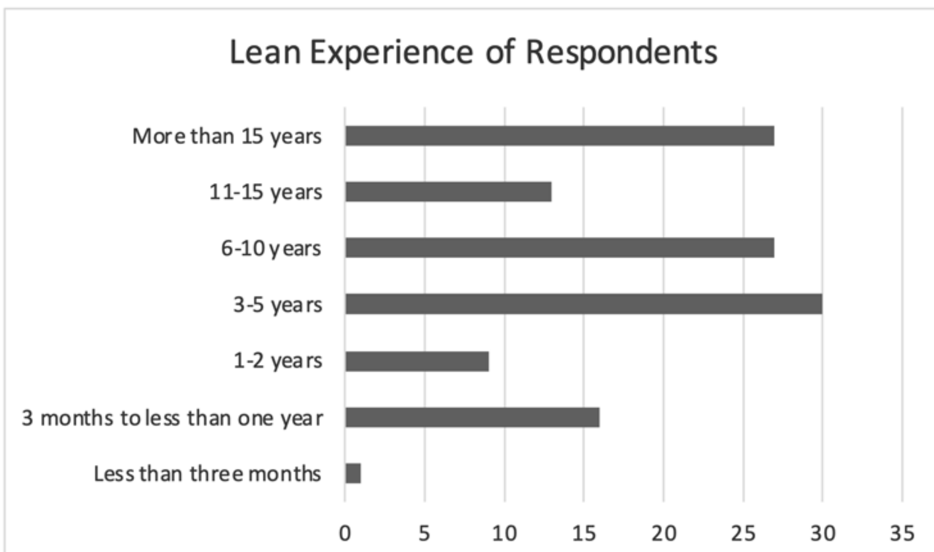

Figure 3. Lean Experience of Survey Respondents

One of the parameters that the user can set when using missForest is the number of node trees. The default value is set to 100. The initial runs were performed with the number of nodes set to 100 to determine the amount of run time and iterations that would be required. With the number of trees set to 100, each iteration took approximately 22-25 seconds to run, and the algorithm required four iterations to find the solution. When the number of trees was set to 200, the algorithm required three iterations and took 43-47 seconds to run. The out-of-box error estimate (OOBEE) provided by the algorithm when using 200-node trees was slightly better than when using 100. Further, when utilizing 500-node trees, the computational time was significantly larger, at about 110 seconds per iteration, and required three iterations. Also, the OOBEE was not better than the result when using

200-node trees. Considering the difference in computational time compared to the OOBEE, it was decided to utilize 200-node trees.

There are many algorithms documented in the literature capable of handling categorical data. Ahmad and Khan (2019), Ganti et al. (1999), Zhang et al. (2000), San et al. (2004), and Gan et al. (2009) documented various approaches to clustering categorical data. Chaturvedi et al. (2001) proposed the K-modes clustering procedure based on the traditional K-means procedure. The K-modes algorithm was designed to derive clusters from categorical data by explicitly optimizing a loss function. It is nonparametric because it does not make any distributional assumptions about the data, and it circumvents the need to define ad hoc distance measures on the categorical data to be clustered. K-modes performed at least as well as other categorical classification methods while being much less computationally expensive.

When utilizing most partitioning style clustering algorithms (such as k-modes), the user must select the number of partitions (clusters) for the algorithm to use. This is generally seen as one of the main drawbacks of partition-based clustering algorithms because it requires the user to have advanced knowledge of the dataset to assume an appropriate number of clusters reasonably. In this case, it is desired to identify three clusters in the data relating to low, medium, and high values of the questions related to lean implementation.

Based on the information for this research, the K-modes algorithm was selected and implemented in R. This decision was made primarily because of the widespread use and commonality of the algorithm. It is a common algorithm for clustering categorical data and is readily available in many software languages. This work was performed in R version 3.5.3. The klar and missForest packages were installed in R and used for this work for clustering and imputation, respectively.

3. Results

The algorithm identified three clusters corresponding to low, medium, and high values for many lean implementation factors. Figure 4 shows the number of data points in each cluster. The x-axis represents the sequential observation number of each data point. The y-axis denotes the cluster assignment and the number of points in each cluster. As shown, cluster 3 had the highest number of points assigned to it, with 1984. Cluster 2 had 1181 points, and cluster 3 had 535 points.

One interesting note about Figure 4 is that there does appear to be a grouping for some of the data points related to the observation number for clusters 1 and 2. The observation numbers were sequential based on the date and time the survey was conducted. It may be because, as individuals completed the survey, their peers and colleagues could see that they had completed it through LinkedIn, prompting them to complete it themselves. If this were true, it could lead to individuals with similar professional experiences, perhaps even within the same organization, completing the survey within a short time of each other.

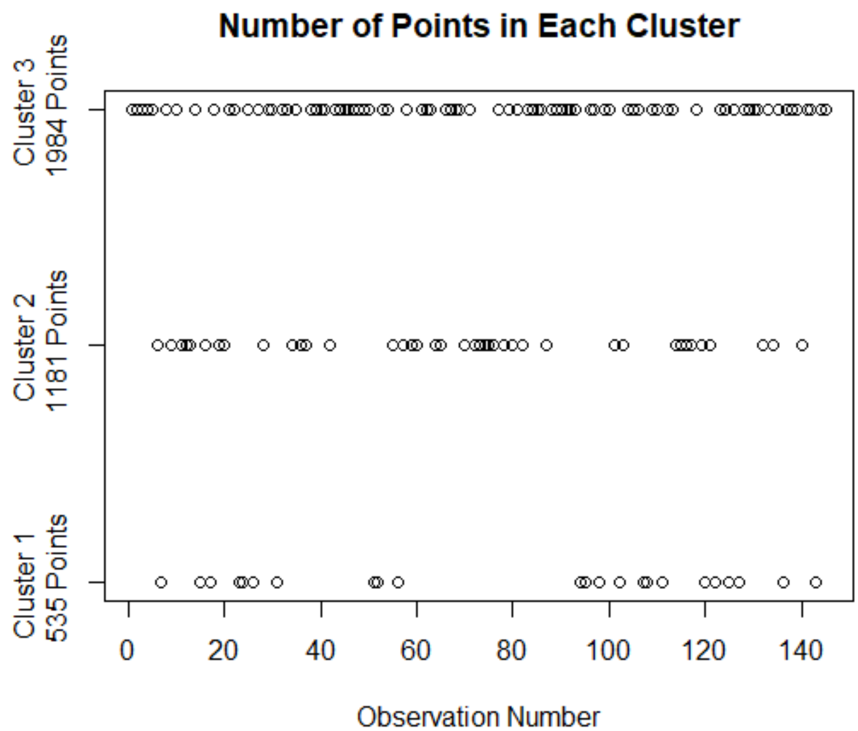

Figure 4. Number Of Points in Each Cluster

The analysis results are provided in Table 1 for each of the survey questions used in the analysis. In addition, the number of missing data points from the data set that was used, after the initial data cleaning described earlier, is provided, as well as the OOBEE from the missForest imputation, the mode value for each question and cluster, and the partial R2 for each question that was determined using regression.

The OOBEE provided by missForest is the proportion of falsely classified (PFC) entries of the imputed dataset (Stekhoven & Buhlmann, 2011). Good performance of the missForest algorithm leads to an OOBEE close to 0, while bad performance produces an OOBEE close to 1. The number of missing data points are relatively low, and even though some of the OOBEE are quite high, when considering the low number of points being imputed, an error of this size is still preferable to the loss of data that would occur if those observations were eliminated from the analysis Stekhoven & Buhlmann (2011).

The cluster modes indicate the mode value for each question in the specified cluster. For most of the questions of interest, the responses were based on a five-point Likert scale where 1 indicates a low score and 5 a high score. Other questions were slightly larger but still had lower values represented by smaller numbers, and higher values represented by larger numbers. Other questions, such as "In what region do you live?" do not follow this same approach and will be discussed separately.

Question a shows that the three cluster lines correlate to high, low, and medium values. The mode value for cluster 1 is five, for cluster 2, the mode value is two, and for cluster 3, the mode value is three. The remaining questions also highlight that other pertinent questions indicate a similar high, low, and medium classification related to the clusters. Beginning at question m, even though clusters 2 and 3 have a mode value of four, cluster 1 has a mode value of seven, indicating a higher level of lean experience coinciding with question a. Additionally, questions q through ay follow this same pattern of cluster 1 being the higher value, cluster 2 being the lower value, and cluster 3 being the medium value. Although in some of these, while the mode values for cluster 2 and cluster 3 are the same, the higher value still corresponds to cluster 1.

Another interesting note involves the mode values for question f. The mode value for cluster 1 is 11, and for cluster 2 is 23. The mode value of eleven represents the consulting industry, while the mode value of 23 represents the manufacturing industry. As shown in Table 1, the mode value for question f in cluster 1 is the consulting industry, while the mode value for question f in clusters 2 and 3 is the manufacturing industry. This could indicate several things, such as consultants may have a more positive outlook. Alternatively, consultants generally only see a small snapshot of what an organization is truly like and do not experience day-to-day life as those in the organization. Alternatively, consultants can better identify the small and large things within an organization that contribute to success (or lack thereof) and better see them objectively.

Some other items to point out are that most respondents were from North America (question e). Most of the respondents were male (question c). Most respondents work in production or operations (question g). Most of the respondents have a graduate degree (question h). In addition, most respondents have over 20 years of work experience (question i). Since these populations constituted most of the responses, this analysis could not distinguish how these factors may affect lean implementation.

The last information presented in Table 1 is the results of the stepwise regression performed on the same data set. In this analysis, the response variable was question a. The selected explanatory variables are denoted by having their partial R2 value listed. Those with an asterisk (*) were identified as one of the top four explanatory variables. As expected, all four explanatory variables relate to the clusters presented.

Table 1. Imputation and Clustering Results

Question		Number of Missing Data Points in the Data Set	Imputation OOB Error Estimate	Cluster 1 Mode	Cluster 2 Mode	Cluster 3 Mode	Regression Model Partial R^2
a	The Lean methodology is deeply rooted in the culture of my organization.	0	0	5	2	3	Regression Model Response Variable
b	Has the original culture of your organization changed after Lean implementation?	21	0.2419	1	1	1	NA
c	What is your gender?	4	0.1418	1	1	1	NA
d	What is the existing infrastructure for Lean implementation in your organization?	0	0	5	3	4	NA
e	In which region do you live/work?	0	0	1	1	1	0.0214
f	In which industry do you work?	1	0.6319	11	23	23	NA

Question		Number of Missing Data Points in the Data Set	Imputation OOB Error Estimate	Cluster 1 Mode	Cluster 2 Mode	Cluster 3 Mode	Regression Model Partial R^2
g	Which of the following most accurately describes your primary functional work area?	0	0	19	19	19	NA
h	What best describes your level of education?	0	0	7	7	7	NA
i	How much work experience do you have?	0	0	5	5	5	0.0224
j	Which of the following most accurately describes your occupational title in your company or organization?	0	0	1	19	14	NA
k	How many total employees are in your company (all branches)?	2	0.7272	6	8	8	NA
l	What are the annual revenues of your company/organization (in US dollars)?	0	0	10	9	10	0.0089
m	How much experience do you have in Lean?	0	0	7	4	4	0.0066
n	How many kaizen/lean events have you participated in?	0	0	5	5	5	NA
o	What is the average duration of lean projects in your organization?	4	0.3333	6	6	6	NA
p	How are projects executed in your organization?	3	0.3521	1	3	3	NA
q	When you provide lean training, how many days is the training?	3	0.8521	7	2	3	NA
r	What proportion of your organization has received lean training?	2	0.7832	11	3	1	*0.2534
s	My group is given the authority to make decisions related to their work.	7	0.4637	5	4	4	NA
t	We are always making small improvements in our process.	7	0.4855	5	4	4	*0.0336
u	Managers encourage proactiveness from their employees.	7	0.5217	5	3	4	NA
v	Procedures are updated when changes are implemented.	7	0.5362	5	4	4	NA
w	My group is involved in the development of process metrics.	7	0.5580	5	3	4	0.0058
x	Management demonstrates dedication and active commitment to initiatives undertaken.	7	0.4855	5	4	4	NA
y	We follow up to make sure improvements continue.	7	0.5507	5	4	4	NA
z	My group understands the difference between value added and non-value-added activities.	7	0.5217	5	4	4	NA
aa	Failures are seen as an opportunity for improvement.	7	0.5580	5	3	4	*0.45

Question		Number of Missing Data Points in the Data Set	Imputation OOB Error Estimate	Cluster 1 Mode	Cluster 2 Mode	Cluster 3 Mode	Regression Model Partial R^2
ab	My group is involved in defining value added steps for the product.	7	0.5507	5	4	4	NA
ac	Batch sizes have been aggressively reduced.	15	0.6308	5	2	3	NA
ad	The "Just-in-Time" concept is a part of daily routine in the workplace.	14	0.5115	5	2	4	NA
ae	A kanban system is used for flow.	15	0.5846	5	3	4	*0.0836
af	Work in process (WIP) between workstations is limited and actively minimized.	14	0.4885	5	3	4	NA
ag	Finished products or services are shipped or provided immediately to the customer.	14	0.5191	5	4	4	NA
ah	Value stream mapping is undertaken to understand how activities create value for the customer.	16	0.5581	5	3	4	NA
ai	Improvements from the value stream mapping process are implemented as planned.	16	0.5039	5	3	4	NA
aj	The technique 5S is used to organize workstations.	16	0.5039	5	4	4	NA
ak	Training programs are an integral part of an employee's development at the workplace.	16	0.4264	5	4	4	NA
al	Pareto analysis is used to prioritize potential causes of problems.	16	0.5039	5	3	4	NA
am	Fishbone diagrams are used to brainstorm potential causes of waste or defects.	16	0.5194	5	4	4	NA
an	Improvements are standardized and documented through standard operating procedures (SOPs)	16	0.5736	5	3	4	NA
ao	SIPOC diagrams are created to understand all aspects of the process.	16	0.5039	5	3	4	NA
ap	Waste analysis and poka-yoke are performed to identify and reduce/eliminate waste.	16	0.6357	5	3	4	NA
aq	A3 problem solving	16	0.5194	5	3	4	NA
ar	SMED is used to reduce changeover time and respond effectively to customer demand.	16	0.4806	5	3	4	NA
as	A scheduling system decides how much is produced at each workstation.	23	0.6230	5	4	4	NA
at	Original contract deadlines are met for every shipment.	23	0.5410	5	3	4	NA
au	Process standards are used throughout the organization at each workstation/workplace.	20	0.4080	5	3	4	NA

Question		Number of Missing Data Points in the Data Set	Imputation OOB Error Estimate	Cluster 1 Mode	Cluster 2 Mode	Cluster 3 Mode	Regression Model Partial R^2
av	Corrective actions are carefully evaluated in relation to customer value.	23	0.4590	5	4	4	NA
aw	A system to communicate customer feedback throughout the organization is present.	17	0.4844	5	4	4	NA
ax	Customer requirements are clearly communicated at each stage in the journey of the product/service, from concept to delivery to the customer.	17	0.4609	5	2	4	NA
ay	My group understands how the customer uses the product/service.	17	0.5234	5	4	4	NA
az	How often do you gather the voice of the customer?	18	0.8740	4	1	6	0.0064

4. Conclusions, Limitations, and Future Research

The method proposed, using a k-modes clustering approach to identify success factors critical to the successful implementation of lean, is a viable approach. This research methodology was successful in identifying three clusters corresponding to low, medium, and high degrees of implementation, along with implementation factors that corresponded to low, medium, and high implementation. This information could be used in the future to help monitor an organization’s lean implementation and provide feedback on areas to focus on to help increase the degree of implementation.

As with any research, there are limitations. When considering an analysis of a very large population of people, a large sample size is typically desired. The survey used in the execution of this research utilized 196 responses. Of those 196, 51 were removed in the initial cleaning because over 50% of the questions were unanswered. After this initial cleaning, 6.8% of the total dataset was still missing. Even though 6.8% of the missing data was imputed, when considered along with the 51 responses removed, the amount of data obtained from the survey should be considered a limitation. This could be due to the survey’s length. The survey was extremely comprehensive, which could have led to survey fatigue. Another limitation to highlight is the overwhelming number of respondents from North America and Europe. Since this research aimed for a global view, the limited number of respondents from other regions needs to be noted. One factor that may have affected this is that the survey was only offered in English, which could have limited the ability of people in other regions to respond. Additionally, most people responding to the survey reported extensive work experience, with only two reporting less than two years’ experience. While obtaining responses from experienced people is generally a positive outcome, having a very small number of less experienced people responding can prevent the capture of diverging perspectives. These diverging perspectives can often be used to gain insights that otherwise go unnoticed.

As mentioned previously, this work could be used as the training set for a supervised learning algorithm. Organizations could employ the supervised algorithm to monitor lean implementation preparedness and execution while making recommendations on areas of focus. Additionally, a follow-on survey that is more targeted in its approach could be created, with fewer questions, distributed to a wider audience, and made available in multiple common languages. This could result in a higher, more diverse response rate and enable the creation of a higher fidelity training set utilizing the clustering method described.

5. Disclaimer Statements

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Conflict of Interest: None

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A MODIFIED INDIVIDUAL MEASUREMENTS CHART FOR MONITORING THE AVERAGE OF 20 TO 40 CORRELATED STREAMS

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Abstract

Modern manufacturing processes often use parallel stations to increase production, in a setup known as multiple-stream processes (MSPs). Monitoring these processes is difficult because using separate control charts for every stream is impractical. Although Group Control Charts simplify this by plotting only the maximum and minimum values, most existing methods assume that the streams are independent. MSPs are more likely to be correlated than not owing to common raw materials or environmental factors, which make standard control limits inaccurate. This research characterizes the statistical behavior of correlated multiple-stream processes, specifically for 20–40 streams. Using Monte Carlo Simulations and an Augmented Face-Centered Composite Design, a mathematical model was developed to predict the in-control Average Run Length (ARL_0). The fitted model was validated and used to generate a predictive equation for the control limit width (L) to maintain the target ARL_0 of 370.4. The study proposed tables of appropriate values of (L) for $20 \leq m \leq 40$ streams, enabling the effective monitoring of correlated streams without incurring excessive false alarms.

Keywords: *Multiple-Stream Processes; Group Control Chart; Correlated Streams*

1. Introduction

Statistical Process Control (SPC) has been an essential tool in quality engineering since the pioneering work of Shewhart (1931). Designing a control chart requires specification of the half-width factor (L), which determines the distance between the centerline and control limits. This parameter affects the long-term performance of a control chart. In traditional applications of Shewhart control charts, the value of L is set to 3, and the resulting limits are referred to as 3-sigma limits. This translates to an in-control average run length (ARL_0) of 370.4, assuming that the charted statistics are normally distributed.

The evolution of modern manufacturing is driven by the constant need for efficiency, which is often achieved through parallel processing. Multiple-Stream Processes (MSPs), in which identical items are simultaneously produced across parallel stations, are now standard across industries, ranging from pharmaceutical filling to high-speed injection molding and textile spinning. As noted by Lanning et al. (2002), such processes can easily involve 20 or more filling heads, creating an environment that challenges the traditional quality control methods. An MSP is defined as a process that generates multiple streams of output, and a critical, often overlooked characteristic of these systems is the correlation (ρ) between streams. As described by Mortell and Runger (1995), streams in MSPs rarely operate independently; they share common causes, such as batches of raw material, ambient temperature, or hydraulic pressure, that induce correlation (ρ) across outputs. While the

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statistical monitoring of a single stream is well documented, MSPs introduce a "dimensionality curse." Maintaining separate control charts for five or more individual streams is impractical and statistically inefficient because it inflates the overall type I error rate (Montgomery, 2020).

Currently, there are no established half-width values (L) for monitoring processes with $m > 20$ correlated streams. The primary challenge lies in the complex interaction between the number of streams (m) and the correlation (ρ) between them. In this study, corrected L values for the individual measurement group charts are proposed for monitoring the average of $20 \leq m \leq 40$ correlated streams.

2. Literature Review

Beyond machine design, the definition of MSP extends to operational setups. For example, a production line might use several identical machines in parallel to meet high demand, or multiple inspectors might simultaneously check the same type of product. Abdulaziz et al. (2019) also noted that using fixtures to hold and machine multiple parts technically creates a multiple-stream process. Furthermore, Epprecht (2015) pointed out that continuous processes, such as textile manufacturing, where quality is measured at various points simultaneously, can be considered MSPs.

From a quality control perspective, these multi-stream processes share two main features: all units produced have the same engineering specifications, and the streams can be independently adjusted. However, as noted by Epprecht (2015), despite how common these processes are, the amount of research dedicated to monitoring them is still limited, indicating an opportunity for new studies.

2.1. The Group Control Chart (GCC) Framework

The simplest way to monitor an MSP is to use a separate chart for each stream as suggested by Meneces et al. (2008). However, if a process has many streams, managing dozens of charts becomes impractical. To address this, Boyd (1950) proposed the Group Control Chart (GCC). These charts remain the standard method for monitoring MSPs, as discussed by Burr (1976), Pyzdek (1991), and Montgomery (2020). Boyd’s method works by filtering the data, which means that instead of plotting every point for every stream, it plots only the maximum and minimum values. This method follows a very simple logic: if the maximum and minimum values are within limits, then all values from the other streams are also within limits.

2.2. The False Alarm Problem

The main weakness of the traditional GCC is the reduction in ARL0 owing to the increased number of streams. Monitoring a process with the original value of $L = 3$ results in an excessive number of false alarms. Nelson (1986) warned about this problem, noting that using standard 3-sigma limits makes the chart unreliable. Grimshaw et al. (1999) showed that for an MSP with identical streams, the standard 3-sigma limits are too narrow. If the limits are not increased, the In-Control Average Run Length (ARL0) decreases significantly. Figure 1 shows ARL0 for different numbers of streams.

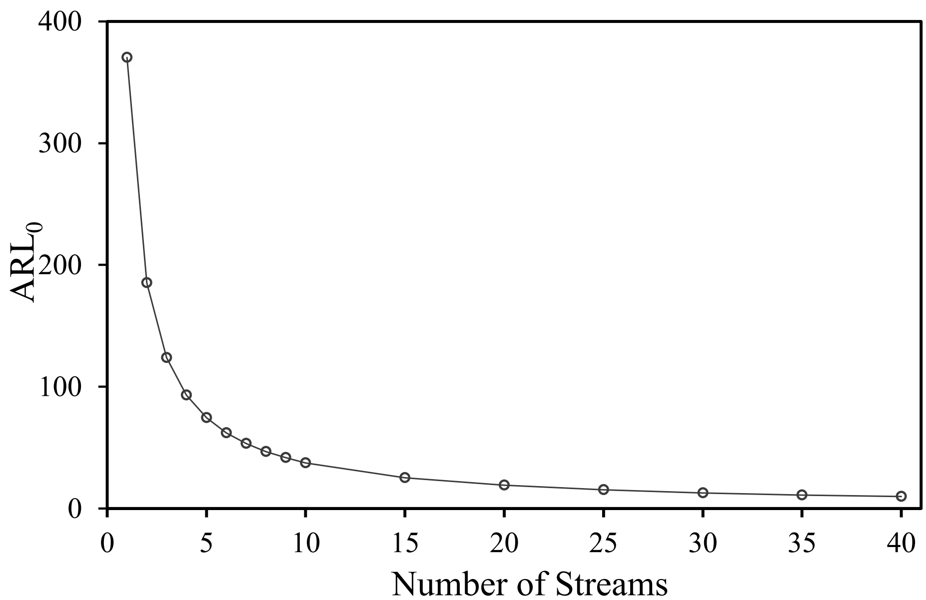

Figure 1. Effect of the Number of Streams on ARL_0. Grimshaw et al. (1999)

The impact of maintaining the standard 3-sigma limit is severe; for example, for a single-stream process, ARL0 is 370.4. However, in a process with 40 streams (the maximum number of streams in this study), ARL0 decreased to approximately 10. This means that the chart indicates a false alarm for every 10 samples on average, which is unacceptable for production. To fix the inflated false-alarm rate, the half-width factor (L) must be adjusted to maintain an ARL0 of 370.4. However, Grimshaw et al. (1999) assumed that the streams are independent (ρ = 0) and the plotted statistic is normally distributed. Table 1 displays the corrected values for L measured in standard deviation units.

Table 1. Correction Required to Obtain an Equivalent ARL_0 = 370.4. Grimshaw et al. (1999)

m	1	2	3	4	5	10	15	20	25	30	35	40
L	3.000	3.205	3.320	3.399	3.460	3.642	3.745	3.817	3.872	3.916	3.953	3.985

2.3. Multiple Streams with Correlation

To address the limitations of assuming independent streams, Ribas and Weheba (2024) developed a mathematical model to estimate the ARL0 through extensive Monte Carlo simulations. Each simulation run was replicated 526,000 times. The authors followed a Response Surface Design to estimate the average run length for up to 20 correlated streams. Based on their simulation studies, they proposed adjusted values for the half-width factor (L) necessary to maintain the target ARL0 of 370.4.

3. Research Methodology

To evaluate the performance of the control charts and the proposed corrected control limits, a Monte Carlo Simulation was constructed within the RStudio environment. A code was developed to calculate the in-control Average Run Length (ARL_0). The simulation parameters were first established, specifically the half-width (L), number of streams (m), and correlation coefficient (ρ). To represent the Xr statistics for each run, a total of N = 50,000 measurements from each stream were generated from a standard normal distribution. The simulation code subsequently identifies the maximum and minimum values in each set and compares them with the limits (± L). A different seed is generated at the start of each run. The first occurrence of a limit violation defined the run length. The ARL_0 was calculated as the mean of all the simulated runs. Following the geometric distribution properties cited by Montgomery (2020), t = 526,000 replications were executed to ensure an estimation precision of ±1.0 at the 95% confidence level. The process flow for the ARL_0 simulation is shown in Figure 2.

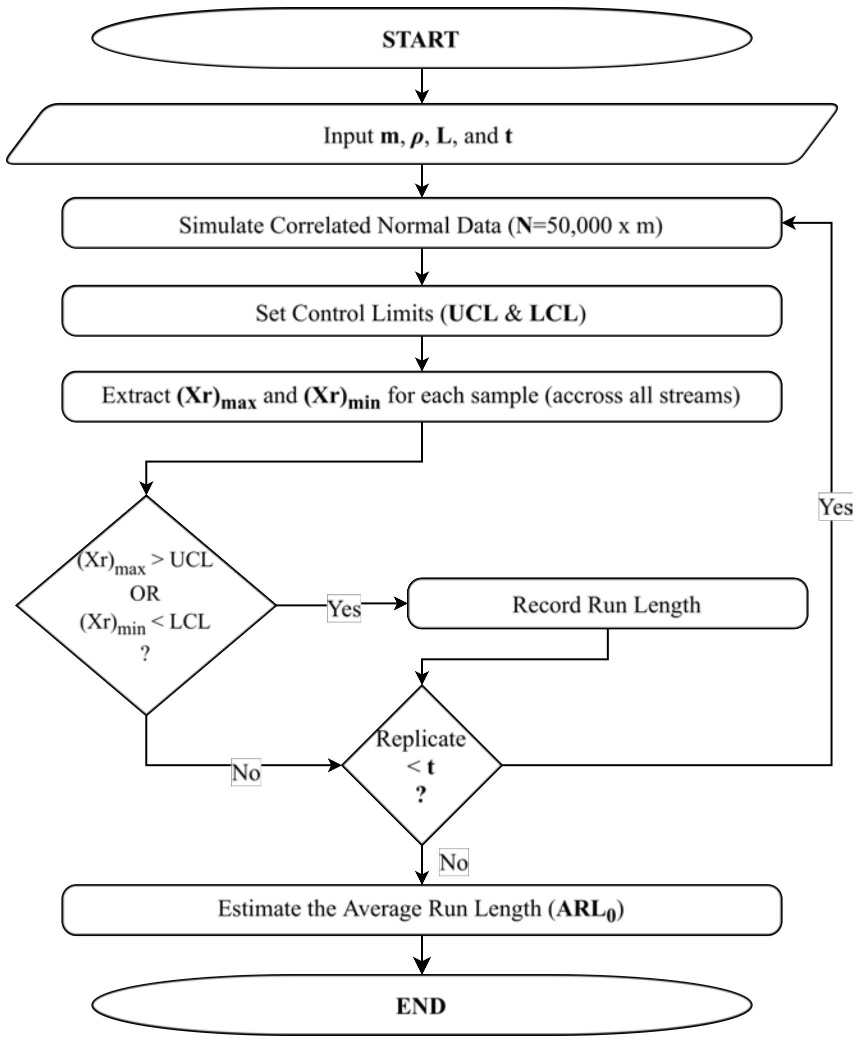

Figure 2. Simulation Flowchart for ARL_0. Schamburg and Brown (2004)

To accurately model the non-linear relationship of the in-control Average Run Length as a function of the half-width factor, number of streams, and level of correlation, a Face-Centered Composite Design (FCCD) was selected and subsequently augmented to enhance the prediction capability (Montgomery, 2017). The Design-Expert v25.05 (2025) software was used to generate the design space and to determine the augmented runs following the I-optimality criteria.

Table 2 lists the design factors and their selected levels. The number of streams (m) is within 20–40 streams. The correlation factor (ρ) varies from 0.0 (independence) to 0.8 (high correlation) to capture the effect on in-control performance (ARL_0). The half-width (L) was examined within the range of 3.5 to 4.1. This interval is selected to ensure that the target ARL_0 can be interpolated within the design space.

Table 2. Factors, Levels, and Range

Factors	Symbol	Type	Low (-1)	High (+1)
Number of Streams	m	Numeric (Discrete)	20	40
Correlation	ρ	Numeric (Continuous)	0.00	0.80
Half-Width	L	Numeric (Continuous)	3.50	4.10

4. Simulation Validation

The simulated results were compared with theoretical values established by Grimshaw et al. (1999). Table 3 presents a comparative analysis of the simulation performance with half-width L = ±3 and correlation ρ = 0 for different numbers of streams (m). As indicated by the percentage error reported in the last column, the simulated results were well within the theoretical values.

Table 3. Comparison of Theoretical vs. Simulated ARL_0 values (L = ±3, ρ = 0)

Streams (m)	Theoretical	ARL_0 (Simulated)	Error (%)
2	185.436	186.070	0.342%
3	123.791	123.838	0.038%
4	92.968	93.049	0.087%
5	74.475	74.452	-0.031%
6	62.146	62.206	0.096%
7	53.340	53.402	0.115%
8	46.736	46.805	0.150%
9	41.599	41.590	-0.020%
10	37.489	37.484	-0.013%
15	25.161	25.202	0.162%
20	18.998	18.990	-0.042%
25	15.300	15.302	0.009%
30	12.836	12.833	-0.023%
35	11.076	11.062	-0.124%
40	9.756	9.761	0.055%

4.1. Mathematical Modeling

A prediction-oriented I-Optimal Design was utilized. As shown in Table 4, the initial Face-Centered Composite Design was augmented by adding eight points (21–28) to meet the optimality criteria. These points are placed inside the design space. The results were analyzed using Design-Expert v25.05 (2025). Residual analysis indicated the need for transformation to stabilize the error variance. A power transformation in the form y = (ARL0)−0.25, was applied to the response data.

Table 4. Experimental Design Matrix and Results for ARL_0 (FCCD + Augmented Runs)

Run	Streams (m)	Correlation (ρ)	Half-Width (L)	ARL_0
1	20	0	4.1	1209.094
2	20	0.8	4.1	2254.182
3	30	0.4	3.8	254.572
4	30	0.8	3.8	551.798
5	40	0.8	4.1	1445.325
6	40	0.8	3.5	166.287
7	30	0.4	3.8	253.650
8	40	0.4	3.8	195.011
9	20	0.4	3.8	369.853
10	40	0	3.5	54.215
11	20	0.8	3.5	244.588
12	30	0.4	3.5	83.705
13	30	0.4	3.8	253.638
14	30	0.4	3.8	253.581
15	20	0	3.5	107.806
16	30	0.4	3.8	253.873
17	30	0	3.8	230.503
18	40	0	4.1	605.309
19	30	0.4	3.8	253.686
20	30	0.4	4.1	855.387
21	35	0.6	3.95	503.131
22	20	0.4	3.5	119.935
23	35	0.2	3.65	112.113
24	25	0.2	3.95	516.885
25	40	0.4	4.1	653.587
26	40	0.4	3.5	65.193
27	40	0	3.8	173.264
28	25	0.6	3.65	213.839

Table 5 presents the results of the analysis of variance (ANOVA) for the transformed values (y). As shown, the reduced model was highly significant, with a p-value < 0.0001. An examination of the residuals revealed that the power transformation successfully stabilized the error variance. No other violations of ANOVA assumptions were detected. The most critical finding was the three-factor interaction involving m, ρ, and L. This result confirms that the effect of the half-width factor cannot be determined without knowing the number of streams and the level of correlation between them. In other words, the effect of L depends on a specific combination of m and ρ. The Lack of Fit is not significant at the 5% level. Both the R2 and Adjusted R2 are close to 1.0, meaning the model explains almost 100% of the variability in the transformed response.

Table 5. ANOVA for Transformed Values of ARL_0

Source	Sum of Squares	DOF	Mean Square	F-value	p-value
Model	0.0825	21	0.0039	263400	< 0.0001
Streams (m)	0.0002	1	0.0002	13069.72	< 0.0001
Correlation (ρ)	0.0002	1	0.0002	11616.65	< 0.0001
Half-Width (L)	0.0135	1	0.0135	902000.00	< 0.0001
$m\rho$	0.0003	1	0.0003	19319.45	< 0.0001
mL	0.0002	1	0.0002	10096.11	< 0.0001
ρL	0.0009	1	0.0009	58613.90	< 0.0001
m^2	2.07E-07	1	2.07E-07	13.86	0.0098
ρ^2	0.0005	1	0.0005	36466.49	< 0.0001
L^2	0.0001	1	0.0001	5248.99	< 0.0001
$m\rho L$	0.0000	1	0	2598.33	< 0.0001
$m^2\rho$	2.46E-07	1	2.46E-07	16.45	0.0067
m^2L	1.82E-09	1	1.82E-09	0.12	0.7392
$m\rho^2$	0.0000	1	0	1376.16	< 0.0001
mL^2	4.99E-07	1	4.99E-07	33.44	0.0012
ρ^2L	0.0001	1	0.0001	3524.56	< 0.0001
ρL^2	1.58E-06	1	1.58E-06	105.97	< 0.0001
m^3	2.75E-07	1	2.75E-07	18.45	0.0051
ρ^3	0.0000	1	0	1506.53	< 0.0001
$m^2\rho^2$	4.74E-07	1	4.74E-07	31.73	0.0013
m^2L^2	2.93E-07	1	2.93E-07	19.62	0.0044
m^4	1.81E-07	1	1.81E-07	12.15	0.0131
Residual	8.95E-08	6	1.49E-08		
Lack of Fit	4.68E-08	1	4.68E-08	5.47	**0.0664**
Pure Error	4.27E-08	5	8.55E-09		
Cor Total	8.25E-02	27			

The Cube Plot in Figure 3 depicts the effects of changes in the design factors on the predicted values of the original response. By comparing the ARL0 values at the limits of the design space, the impact of the correlation (ρ) is more noticeable when comparing the top and bottom faces. Specifically, at m = 20 and L = 3.5, increasing the correlation from 0 to 0.8 moves the ARL0 from 107.798 to 244.657, a 127% increase. However, when m = 40 and L = 3.5, the ARL0 increased from 54.225 to 166.273, representing a 206.6% increase. Also, it is worth noting that at ρ = 0 and L = 4.1, implementing more streams in the process resulted in an approximate 50% reduction in the ARL0 (from 1208.6 to 605.381). However, at ρ = 0.8 and L = 4.1, the same increase in the number of streams (m) leads to a significantly smaller reduction of approximately 36% (from 2254.56 to 1444.7).

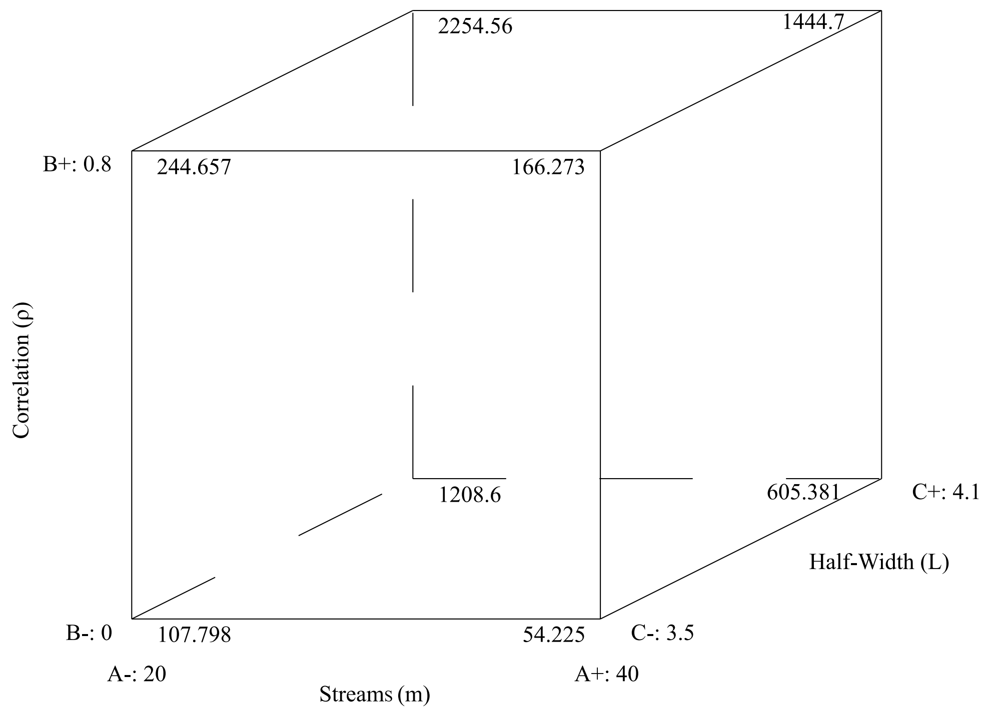

Figure 3. Cube Plot for ARL_0

4.2. Model Confirmation

Table 6 shows that the model demonstrates high predictive accuracy across the experimental region. For all seven confirmation runs, the predicted mean values fall within the calculated 95% Confidence Intervals. Notably, even at a higher number of streams (m = 38) and varying correlation levels, the difference between the predicted model response and the actual simulation average remains minimal.

Table 6. Confirmation Runs for ARL_0 (Two-sided 95% Confidence Interval, 3 runs-average)

Confirmation Location #	Confirmation runs						
	Stream (m)	Corr. (ρ)	Width (L)	Predicted Mean	Confirmation Runs (Avg)	95% CI Low	95% CI High
1	22	0.1	3.837	366.572	365.930	363.778	369.392
2	23	0.3	3.845	371.161	371.790	369.241	373.093
3	28	0.5	3.859	370.513	370.927	369.448	371.581
4	33	0.1	3.938	369.038	369.853	367.375	370.711
5	33	0.5	3.896	371.026	370.919	369.838	372.219
6	38	0.1	3.972	369.151	371.190	367.232	371.082
7	39	0.6	3.890	367.032	367.557	364.448	369.639

These results support the adequacy of the fitted model and confirm that the developed equation can be reliably used to estimate the ARL_0 for process configurations that are not explicitly included in the original design matrix.

4.3. Tables of recommended Values of L (ARL_0 = 370.4)

The recommended values for the half-width factor (L) to achieve an ARL0 of 370.4 are detailed in Table 7. These factors were derived by setting the response to the target value ARL0 = 370.4 and solving for L across the experimental range of the number of streams (m) and correlation levels (ρ).

Table 7. Values of Half-Width (L) for 20 ≤ m ≤ 40 streams to achieve ARL_0 = 370.4

Number of Streams (m)	Correlation (ρ)								
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
20	3.8176	3.814	3.812	3.809	3.8	3.783	3.753	3.703	3.626
22	3.8425	3.84	3.838	3.833	3.824	3.806	3.774	3.723	3.642
24	3.8642	3.861	3.859	3.855	3.845	3.826	3.792	3.739	3.656
26	3.8834	3.881	3.879	3.874	3.863	3.843	3.808	3.753	3.667
28	3.901	3.899	3.897	3.891	3.88	3.859	3.823	3.765	3.678
30	3.9175	3.915	3.913	3.908	3.896	3.874	3.837	3.778	3.688
32	3.9331	3.931	3.929	3.924	3.911	3.889	3.85	3.79	3.698
34	3.9478	3.946	3.944	3.939	3.926	3.902	3.863	3.801	3.708
36	3.9615	3.96	3.958	3.952	3.94	3.916	3.876	3.813	3.718
38	3.9738	3.973	3.971	3.965	3.952	3.928	3.887	3.824	3.728
40	3.9842	3.983	3.982	3.976	3.963	3.938	3.897	3.833	3.736

5. Conclusions and Future Research

This study successfully characterized the statistical behavior of correlated multiple-stream processes for 20 ≤ m ≤ 40 streams. A mathematical model relating ARL_0 to the half-width (L), number of streams (m), and level of correlation (ρ) was successfully developed using an I-Optimal Response Surface Design. The model was used to create tables of the half-width (L) required to achieve the target ARL_0 of 370.4. Similar tables can be generated for different values of ARL_0 using the fitted model. It is noteworthy that the values of L in Table 7 should not be extrapolated in scenarios involving more than 40 streams. Similar research is required to characterize the relationship when m > 40 streams. The results demonstrated that knowledge of the level of correlation between the streams is useful in setting up a group control chart. A high correlation appears to have a positive impact on the control chart's in-control performance. This impact becomes more pronounced as the process scales up, meaning that the correlation provides the greatest benefit when monitoring a higher number of streams. These authors are in the process of developing another simulation model that can track the average number of points required to detect a shift in the process average when values of the half-width from Table 7 are used.

6. Disclaimer Statements

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Conflict of interest: None

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CRITICAL SUCCESS FACTORS IN NEW PRODUCT DEVELOPMENT

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Abstract

New product development (NPD) plays a critical role in enabling companies to remain competitive in today's global marketplace. However, success in NPD remains highly variable, significantly impacting company performance. This study investigates the critical success factors (CSFs) that enable successful NPD through a worldwide multi-industry survey. Survey responses were analyzed using Kruskal-Wallis non-parametric statistical analysis to rank the CSFs based on importance. The research identified 17 CSFs, categorized into two primary groups: front-to-end execution and supporting elements. Front-to-end execution focuses on robust early-stage activities and methods such as voice of the customer gathering, competitive benchmarking, and applying robust design and manufacturing practices to ensure high-quality outputs. Supporting elements include leadership engagement, team empowerment, accountability, and the organization's experience and knowledge. The findings offer managers a framework to enhance NPD processes, drive project success, and sustain competitive advantage. While the study achieved statistically significant results from an international and multi-industry sample, it acknowledges limitations related to sample distribution across industries and geographic regions. Future research should expand on these findings by developing risk mitigation frameworks or best practices aligned explicitly with the top-ranked CSFs identified in this research.

Keywords: *New Product Development; Critical Success Factors; Kruskal-Wallis*

1. Introduction

New product development (NPD) includes all activities necessary to transform a market opportunity or innovation into a product ready for commercial launch. In today's global marketplace, NPD faces increasing challenges, including balancing complex trade-offs, changing customer expectations, rapid technological advancements, heightened competition, and pressures to reduce time-to-market and costs (Takeuchi & Nonaka, 1986; Leonard-Barton, 1992). Despite these obstacles, customers continue to expect products that offer superior quality and reliable performance throughout their lifecycle.

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Failure to meet these expectations can damage brand reputation and customer loyalty. Studies highlight significant variation in NPD success rates across industries. For example, Cooper et al. (2004a) found that, on average, only 60.2% of NPD projects are commercially successful. Companies in the top 20% achieved 79.5% success, while those in the bottom 20% managed only 37.6%, and 19% of NPD projects are canceled before launch, highlighting inefficiencies and improvement opportunities.

Understanding the critical success factors (CSFs) that distinguish successful NPD initiatives is crucial for companies seeking to improve outcomes and maintain competitiveness. A well-executed NPD process enhances project success rates and improves profitability, market share, and organizational learning (Cooper et al., 1995; Page, 1993). However, despite its importance, relatively little research has explored CSFs for NPD across multiple industries and global contexts. Most prior studies have focused on specific industries or limited geographic areas, leaving a gap that this study seeks to address.

This research reviews existing literature on CSFs to identify factors influencing NPD success. Building upon this foundation, a worldwide multi-industry survey was conducted to assess the relative importance of these factors. The survey responses were analyzed using non-parametric statistical techniques, specifically the Kruskal-Wallis test, to rank the CSFs based on their perceived criticality.

This research aims to develop a practical framework for managers to design, evaluate, or refine their NPD execution structures, methods, and processes. By focusing on the factors most strongly associated with success, companies can better allocate resources, design more robust processes, and create organizational cultures that support innovation and sustainable competitive advantage (Lester, 1998; Kahn et al., 2006).

The paper proceeds as follows: first, a review of relevant literature is presented to provide context for the identified CSFs. Next, the survey methodology is detailed, followed by an analysis of the results. Finally, the paper discusses the grouping of key CSFs through factor analysis and provides recommendations for practitioners and future research directions.

2. Review of Relevant Literature

Research into CSFs in NPD spans several decades, reflecting innovation management's complex and evolving nature. Early studies by Takeuchi and Nonaka (1986) emphasized concurrent engineering and flexible, self-organizing project teams. Their work highlighted six principles, such as overlapping development phases and subtle management control, that remain highly relevant to today's NPD practices. Leonard-Barton (1992) introduced the concept of core capabilities, knowledge, skills, technical systems, managerial systems, and organizational values that influence an organization's ability to innovate successfully. Managing the tension between leveraging existing capabilities and fostering innovation is crucial to NPD success.

Accelerating NPD processes through simplification, parallel processing, and early cross-functional collaboration was studied by Millson et al. (1992). Their findings align with later studies by Page (1993) and Cooper et al. (1995), who found that multidisciplinary teams, formalized NPD processes, and leadership commitment significantly impacted project outcomes. Hart (1993) underscored the multi-dimensional nature of NPD success, noting the importance of financial and non-financial performance measures. Linking competitive strategy, technological innovation, and market orientation to NPD success has remained a critical theme across studies.

Later research continued to refine the understanding of CSFs. Lester (1998) identified senior management commitment, innovative culture, project management practices, and resource allocation as key drivers. Adams et al. (1998) emphasized the importance of organizational learning and market sensing, proposing that tools like Quality Function Deployment (QFD) help cross-functional teams align technical solutions with customer needs.

Supplier integration also emerged as a vital component, with Ragatz et al. (1997, 2002) and Petersen et al. (2005) demonstrating that early and strategic supplier involvement can enhance design quality, reduce costs, and accelerate time-to-market. Ogawa and Piller (2006) further advanced this area by proposing methodologies that integrate customer input into the early stages of NPD to mitigate development risks. Olson et al. (1995) and Keller (2001) further explored the dynamics of cross-functional teams, who found that early integration, communication structures, and functional diversity significantly impact NPD project outcomes.

Boutellier et al. (1998) contributed additional insights on dispersed product development teams, emphasizing the critical role of information technologies in supporting collaboration across geographically distributed teams. They noted that while IT enhances efficiency, face-to-face interaction remains essential during critical knowledge transfer stages. Connell et al. (2001) reinforced the importance of executive direction, project team capability, and the management of both internal and external environmental factors in driving NPD success.

Cooper et al. (2004a, 2004b, 2004c) provided a comprehensive benchmarking of best practices in NPD, identifying high-quality execution, innovation strategies aligned with corporate goals, and robust stage-gate processes as consistent drivers of success across industries. De Brentani and Kleinschmidt (2004) further emphasized the critical role of corporate culture, innovation commitment, and resource allocation in international NPD initiatives.

More recent studies, such as Kahn et al. (2006) and Dubiel et al. (2016), highlight the importance of global discovery management and the need for firms to integrate global market intelligence during early NPD stages. Researchers like Kimita et al. (2018) expanded the focus on reliability by proposing failure mode analysis methodologies for designing highly reliable product-service systems. Similarly, Van Oorschot et al. (2018) emphasized the importance of flexible stage-gate planning, arguing that NPD teams must anticipate and accommodate unknown tasks early in project schedules to improve product profitability.

Literature consistently underscores that successful NPD execution depends on a balanced approach, integrating customer needs, technological capabilities, cross-functional collaboration, robust processes, organizational learning, and proactive leadership. However, despite the depth of research, limited studies address CSFs across a broad range of industries and geographic contexts, creating a gap that this study seeks to fill through a global multi-industry survey.

3. Research Methodology

This study followed a three-stage methodology: developing the survey, conducting and analyzing survey results, and reporting the findings. Figure 1 summarizes the overall research process.

Developing the Survey
Step 1: Identify the research goals and objectives. This study's research goals and objectives were to identify the CSFs in NPD based on survey results from a worldwide multi-industry survey. ***Step 2***: Identify the CSFs found in prior research. The findings outlined 116 CSFs in prior research. Similar success factors were grouped, which reduced the number of CSFs to 36 for the final survey. ***Step 3***: Develop a survey with a ranking scale. Develop demographic and CSFs questions. A 5-point Likert scale was selected (strongly disagree, disagree, neutral, agree, strongly agree).
Conducting and Analyzing the Survey Results
Step 4: Distribute the survey via social media. The researchers posted the survey on relevant LinkedIn social media groups. 240 initial survey responses + 81 follow-up question survey responses + 88 final survey responses. ***Step 5***: Analyze the survey data. Analyze the demographic data to validate the survey responses. A non-parametric statistical analysis, Kruskal-Wallis, was selected to determine the statistical differences in the CSFs based on rank. The research used the Kruskal-Wallis positive z-score to determine the CSFs to focus on in the NPD framework development. ***Step 6***: Conduct Factor Analysis to group similar factors. The study employed factor analysis to sort CSFs by the highest weighted coefficients and group interdependent CSFs.
Reporting and Dissemination
Step 7: Report results and interpret results.

Figure 1. Research Methodology

3.1 Identify the Research Goal and Objectives

The research aimed to identify critical success factors (CSFs) in new product development (NPD) through a global, multi-industry survey.

3.2 Identify the CSFs Found in Prior Research

A literature review identified 116 CSFs, which were later condensed into 36 factors grouped under four categories: NPD process, organizational development, research and development (R&D), and project-specific elements (Table 1).

Table 1. CSFs Determined by the Current Literature

Category	Sub-Tier Category	References Cited
NPD Process	The NPD documentation includes stage/gate criteria and deliverables.	Takeuchi et al. (1986); Page (1993); Lester (1998); Cooper et al. (1995); Cooper et al. (2004c); Kahn et al. (2006)
	All levels of the organization are committed to following the NPD process (i.e., from executive leadership to the working level core team).	Lester (1998); Cooper et al. (1995); Connell et al. (2001); Cooper et al. (2004a); Cooper et al. (2004c); De Brentani et al. (2004); Kahn et al. (2006)
	Performance metrics are used throughout the NPD process to assess projects.	Hart (1993); Cooper et al. (1995); Connell et al. (2001); Cooper et al. (2004a); Cooper et al. (2004c); De Brentani et al. (2004); Kahn et al. (2006)
	The NPD process documents the lessons learned.	Takeuchi et al. (1986); Connell et al. (2001)
NPD Organizational Development	Organizational design and communication structure (e.g., meeting structure, IT system, escalation process) adequately support the NPD project.	Boutellier et al. (1998); Lester (1998); Connell et al. (2001); Cooper et al. (2004a); Kahn et al. (2006)
	The organization has documented design processes for its products or services.	Leonard-Barton (1992)
	The organization has sufficient knowledge and experience in research and development.	Leonard-Barton (1992); Cooper et al. (1995)
	The organization quantifies product or service failure modes throughout NPD.	Kimita et al. (2018)
	The organization has sufficient knowledge and experience in validation testing.	Leonard-Barton (1992); Cooper et al. (1995)
Research and Development	The organization benchmarks the competition during NPD (e.g., products, pricing, and strategies).	Connell et al. (2001); Cooper et al. (2004c)
	Organizational innovation and technology strategy guide NPD projects.	Page (1993); Cooper et al. (1995); Lester (1998); Connell et al. (2001); Cooper et al. (2004a); Cooper et al. (2004b); De Brentani et al. (2004); Kahn et al. (2006)
	The NPD team gathers the VOC (i.e., needs, wants, and problems).	Takeuchi et al. (1986); Adams et al. (1998); Cooper et al. (2004c); Kahn et al. (2006); Ogawa et al. (2006); Dubiel et al. (2016)
	The NPD team uses the VOC to define and develop the product or service throughout the NPD process.	

Category	Sub-Tier Category	References Cited
	Products or services developed in the NPD consistently offer a competitive advantage in the marketplace in terms of performance.	Adams et al. (1998); Lester (1998); Connell et al. (2001); Cooper et al. (2004c); Kahn et al. (2006); Ogawa et al. (2006); Dubiel et al. (2016)
	Products or services developed in NPD consistently offer a competitive advantage in the marketplace regarding the schedule.	
	Products or services developed in NPD consistently offer a competitive advantage in the marketplace in terms of cost.	
	The higher the number of design changes required, the lower the probability of success of the NPD effort.	Cooper et al. (1995).
NPD Project Specific	An incorrect product or process architecture can be selected early in NPD processes.	Millson et al. (1992); Cooper et al. (2004c); Ogawa et al. (2006)
	Leadership/management is fully engaged in the NPD project.	Page (1993); Cooper et al. (1995); Lester (1998); Connell et al. (2001); Cooper et al. (2004a); De Brentani et al. (2004); Kahn et al. (2006)
	The management team drives the scope, expectations, and value proposition of the NPD effort.	Takeuchi et al. (1986); Cooper et al. (1995); Lester (1998); Connell et al. (2001); Cooper et al. (2004a); Cooper et al. (2004c); De Brentani et al. (2004)
	The NPD project has clearly defined requirements and specifications.	Lester (1998); Cooper et al. (2004c)
	The NPD project has stable requirements and specifications that are maintained throughout the development process.	Cooper et al. (2004c)
	Company culture creates an environment where the NPD project team feels empowered to execute the NPD project effectively and efficiently.	Takeuchi et al. (1986); Leonard-Barton (1992); Lester (1998); Connell et al. (2001); Cooper et al. (2004a); De Brentani et al. (2004)
	The company has adequate planning in the early stages of the NPD process.	Millson et al. (1992); Lester (1998); Connell et al. (2001); Cooper et al. (2004b); Kahn et al. (2006)
	NPD projects have realistic and stable project schedules.	Van Oorschot et al. (2018)
	NPD projects have adequate budgets.	Page (1993); Cooper et al. (1995); Lester (1998); Connell et al. (2001); Cooper et al. (2004b); De Brentani et al. (2004)

Category	Sub-Tier Category	References Cited
	The organization appropriately staffs NPD teams with cross-functional team members.	Takeuchi et al. (1986); Leonard-Barton (1992); Millson et al. (1992); Page (1993); Cooper et al. (1995); Adams et al. (1998); Lester (1998); Connell et al. (2001); Keller (2001); Cooper et al. (2004a); Cooper et al. (2004b); De Brentani et al. (2004); Kahn et al. (2006)
	The NPD team has the appropriate structure and tools to support collaboration, integration, and information exchange for effective, efficient decision-making.	Takeuchi et al. (1986); Cooper et al. (1995); Boutellier et al. (1998); Lester (1998); Connell et al. (2001); Cooper et al. (2004a); De Brentani et al. (2004)
	The NPD team thoroughly applies the NPD process and tools to their fullest extent.	Cooper et al. (1995); Cooper et al. (2004a); Cooper et al. (2004c); Kahn et al. (2006)
	The NPD team is accountable for the project's success.	Takeuchi et al. (1986); Leonard-Barton (1992); Cooper et al. (1995); Cooper et al. (2004a)
	The NPD team applies lessons learned and organizational knowledge.	Takeuchi et al. (1986); Leonard-Barton (1992); Lester (1998); Connell et al. (2001)
	The NPD team focuses on robust design methods in the product or process.	Mashhadi et al. (2012)
	The NPD team focuses on superior quality in the product or process.	Cooper et al. (1995); Connell et al. (2001); Cooper et al. (2004c)
	The NPD team focuses on robust manufacturing and assembly methods of products or service delivery.	Millson et al. (1992)
	The NPD team considers the supply base's knowledge and experience with the technology.	Takeuchi et al. (1986); Ragatz et al. (1997); Ragatz et al. (2002); Petersen et al. (2005)
	The NPD team engages suppliers actively in the NPD process.	

The NPD process category emphasized documented stage/gate processes, cross-functional team alignment, and organizational commitment (Takeuchi & Nonaka, 1986; Cooper et al., 1995; Kahn et al., 2006). Organizational development factors included communication structures, IT systems, and capturing organizational knowledge (Leonard-Barton, 1992; Lester, 1998). R&D factors highlighted innovation strategies, market research integration, and competitive benchmarking (Adams et al., 1998; Cooper et al., 2004c).

3.3 Develop a Survey with a Ranking Scale

The survey included demographic questions and 5-point Likert scale rankings for each CSF (1 = strongly disagree to 5 = strongly agree). Identifying the correlation of the variables within a model can give important information with respect to how one variable reacts to the other. Since the model only informs of a linear relationship between two variables, the analysis would be specific to the level of interaction of those two variables.

3.4 Distribute the Survey via Social Media

The survey was distributed via LinkedIn groups related to engineering, manufacturing, and quality management. A total of 240 responses were received, with 118 complete surveys for the initial 26 CSFs, 45 complete surveys for 10 additional CSFs, and 44 complete surveys for a full 36 CSFs validation.

Sample size adequacy was confirmed following the guidelines from Lehmann and D'Abrera (1998), who recommend conservative adjustments for non-parametric tests compared to parametric tests. In addition, GraphPad (2019) provided a one-way ANOVA sample size guide indicating that for five levels (5-point Likert scale), $\alpha = 0.05$, and power = 0.95, a sample size of 38 was required, which increased to 44 after a 15% adjustment. This confirmation is illustrated in Figure 2.

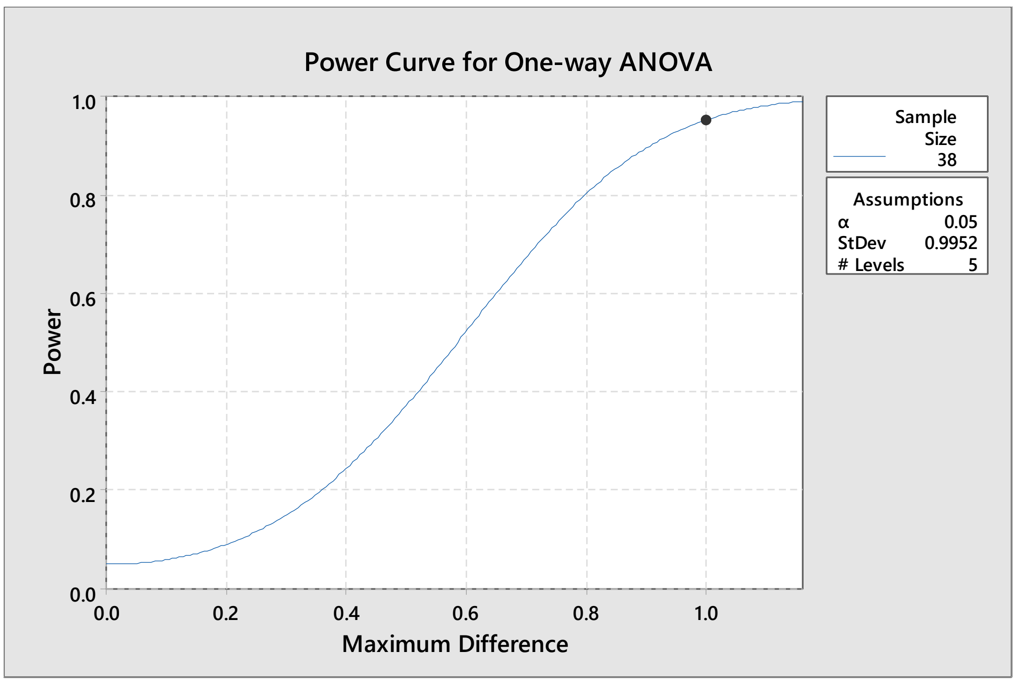

Figure 2. Power and Sample Size for One-Way ANOVA

Further, Unkelos-Shpigel et al. (2015) demonstrated that LinkedIn professional groups are an effective means of reaching industry respondents for empirical survey research, supporting the use of this distribution method in the study.

3.5 Conduct an Analysis of the Survey Data

Demographic data showed that 40.3% of participants had experience with more than 11 NPD projects, and 63.5% had over 11 years of industry experience. In addition, 79.9% worked at companies with a documented NPD process. Participants came from diverse industries, including pharmaceuticals, automotive, engineering services, aerospace, biomedical, and chemical sectors, with broad functional representation (Figures 3–5, Tables 2–6).

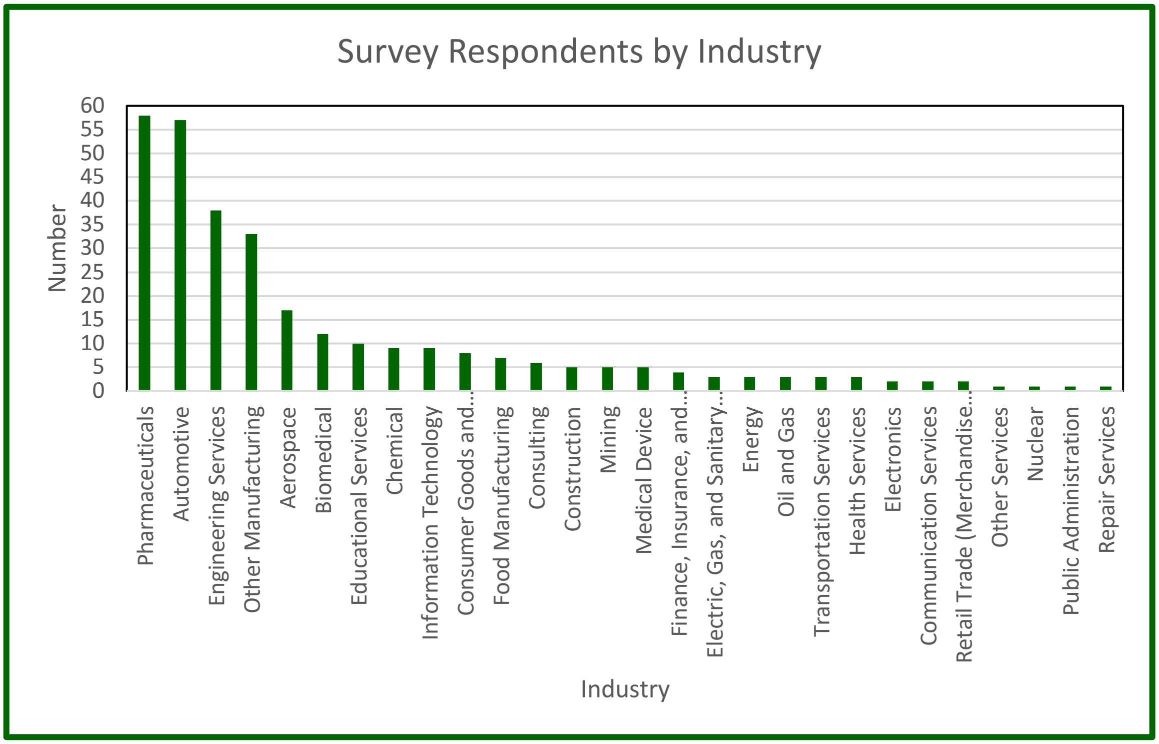

Figure 3. Survey Respondents by Industry

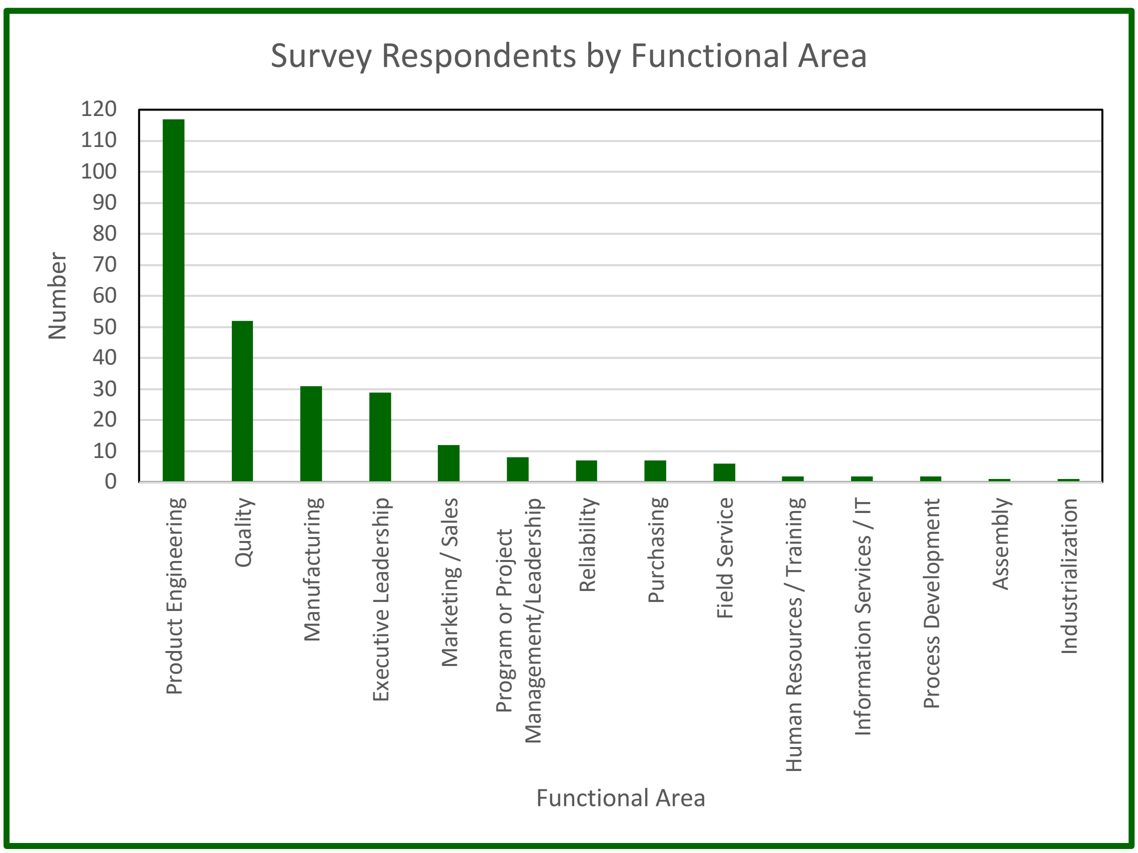

Figure 4. Survey Respondents by Functional Area

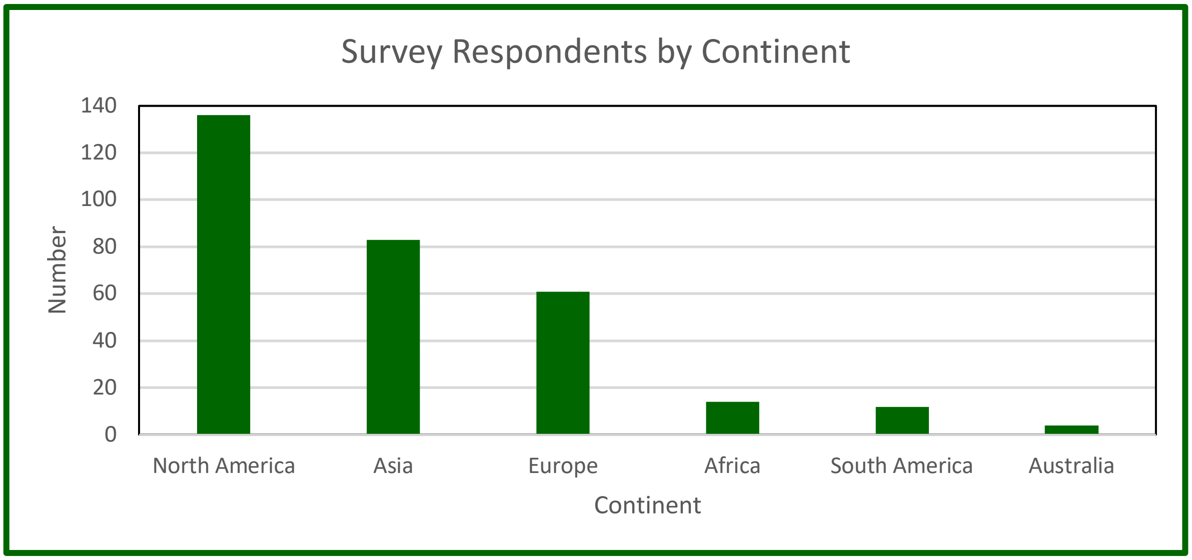

Figure 5. Survey Respondents by Continent

Table 2. Survey Participants by the Number of NPD Projects They Have Participated In

Number Projects	Quantity	Percentages
0	25	7.04%
1-2	58	16.34%
3-5	63	17.75%
6-10	66	18.59%
11-15	28	7.89%
>15	115	32.39%
Total	355	100.00%

Table 3. Survey Participants by Industry Experience

Industry Experience (Years)	Quantity	Percentages
0	4	1.46%
1-2	17	6.20%
3-5	28	10.22%
6-10	51	18.61%
11-15	37	13.50%
>15	137	50.00%
Total	274	100.00%

Table 4. Survey Participants by Company Size (I.E., Number of Employees)

Company Size	Quantity	Percentages
Under 19	26	8.64%
20-49	18	5.98%
50-499	71	23.59%
500-999	29	9.63%
1,000-2,499	35	11.63%
2,500 or more	122	40.53%
Total	301	100.00%

Table 5. Survey Participants by Annual Company Revenue Last Year

Company Annual Revenue	Quantity	Percentages
Under $49,999	14	5.05%
$50,000 - $99,999	12	4.33%
$100,000 - $499,999	22	7.94%
$500,000 - $999,999	19	6.86%
$1,000,000 - $9,999,999	51	18.41%
More than $10M	159	57.40%
Total	277	100.00%

Table 6. Survey Participants by Company Investment in NPD (In Terms of Sales)

Company NPD Investment	Quantity	Percentages
Less than 5%	63	22.66%
5% - 9.9%	52	18.71%
10% - 19%	49	17.63%
20% - 29%	17	6.12%
More than 30%	28	10.07%
Do Not Know	69	24.82%
Total	278	100.00%

Given the non-normality of the Likert data (Figure 6) and the finding of equal variances across CSFs (Figure 7), as determined by the Multiple Comparisons method (Banga & Fox, 2013), the Kruskal-Wallis non-parametric method was selected. This test compared ranks to identify CSFs with statistically higher importance (Table 7).

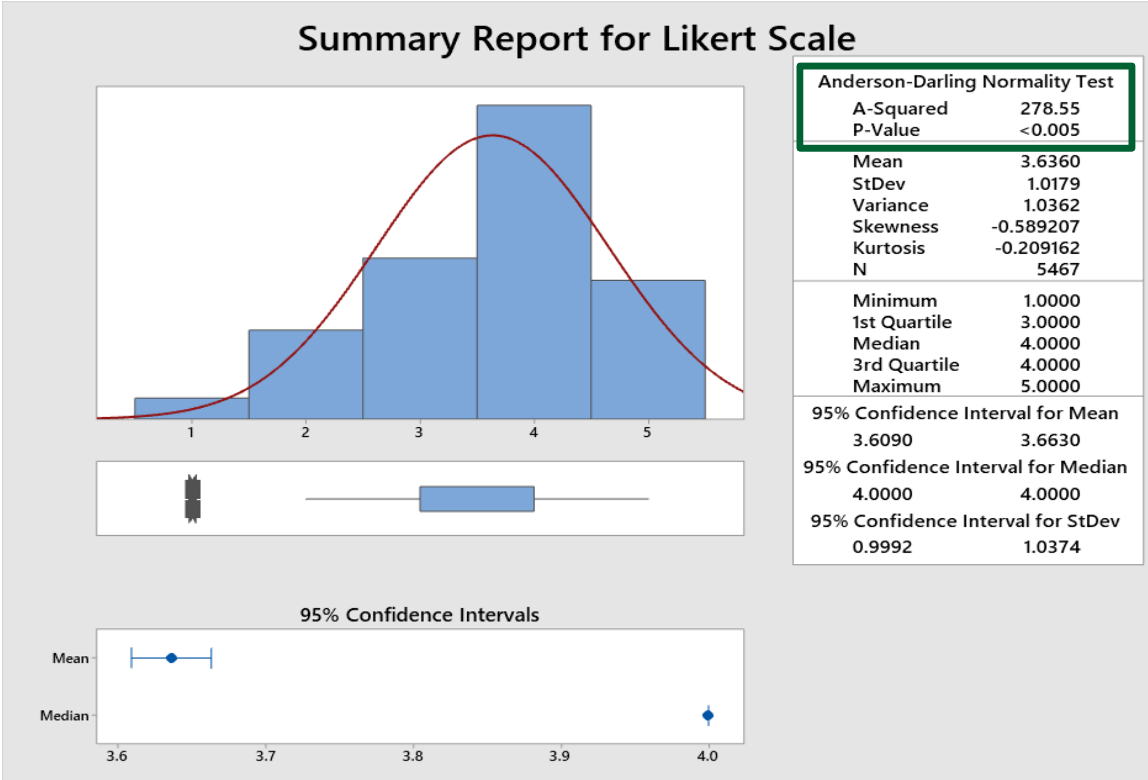

Figure 6. Normality Test

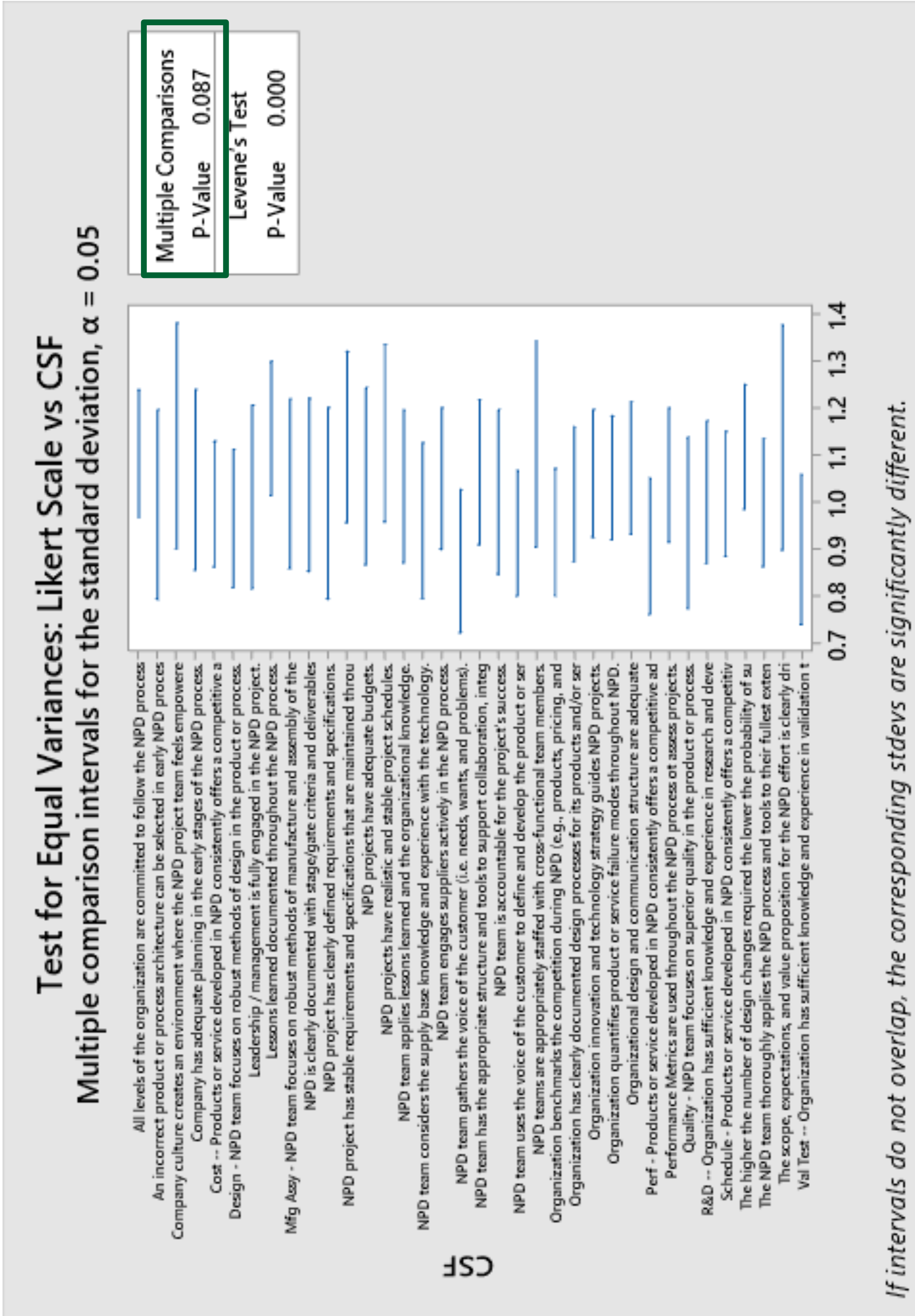

Figure 7. Test for Equal Variances

Table 7. CSFs Rank Results by Kruskal-Wallis

	Survey Results				
CSFs	Rank	N	Median	Mean Rank	Z-Value
The NPD documentation includes stage/gate criteria and deliverables.	1	196	4	3303.6	5.15
The NPD team gathers the VOC.	2	173	4	3127.7	3.33
The NPD team focuses on superior quality in the product or process.	3	162	4	3125.9	3.21
The organization has sufficient knowledge and experience in validation testing.	4	188	4	3085.2	3.11
The organization has sufficient knowledge and experience in research and development.	5	189	4	3016.8	2.51
The NPD team uses the VOC to define and develop the product or service throughout the NPD process.	6	172	4	2987.8	2.14
The NPD team is accountable for the project's success.	7	163	4	2975	1.98
The management team drives the scope, expectations, and value proposition of the NPD effort.	8	91	4	3030.9	1.81
The organization benchmarks the competition during NPD (i.e., products, pricing, and strategies).	9	173	4	2943.7	1.78
Products or services developed in the NPD consistently offer a competitive advantage in the marketplace in terms of performance.	10	173	4	2928.1	1.64
Leadership/management is fully engaged in the NPD project.	11	92	4	2977.5	1.49
The NPD team focuses on robust manufacturing and assembly methods of products or service delivery.	12	162	4	2905.9	1.41
The NPD project has clearly defined requirements and specifications.	13	91	4	2929.3	1.19
The NPD team focuses on robust design methods in the product or process.	14	162	4	2873.9	1.15
The organization has documented design processes for its products or services.	15	188	4	2829.1	0.84
Company culture creates an environment where the NPD project team feels empowered to execute the NPD project effectively and efficiently.	16	88	4	2810.6	0.46
The NPD team considers the supply base's knowledge and experience with the technology.	17	159	4	2786.7	0.43
Organizational innovation and technology strategy guide NPD projects.	18	173	4	2731.9	-0.02
The NPD team applies lessons learned and organizational knowledge.	19	162	4	2650.4	-0.68
The NPD team engages suppliers actively in the NPD process.	20	162	4	2650.8	-0.68

CSFs	Rank	N	Median	Mean Rank	Z-Value
All levels of the organization are committed to following the NPD process (i.e., from executive leadership to the working level core team).	21	197	4	2649.9	-0.76
The NPD team documents lessons learned throughout the NPD process.	22	197	4	2636.6	-0.88
The NPD team has the appropriate structure and tools to support collaboration, integration, and information exchange for effective/efficient decision-making.	23	162	4	2626.1	-0.88
The organization appropriately staffs NPD teams with cross-functional team members.	24	89	4	2556.2	-1.07
Performance metrics are used throughout the NPD process to assess projects.	25	197	4	2613.4	-1.09
Organizational design and communication structure (e.g., meeting structure, IT system, escalation process) adequately support the NPD project.	26	188	4	2564.7	-1.5
An NPD team can select incorrect products or process architecture early in the NPD process.	27	92	4	2444.3	-1.78
Products or services developed in NPD consistently offer a competitive advantage in the marketplace in terms of cost.	28	172	4	2500.1	-1.97
NPD projects have adequate budgets.	29	90	4	2386.6	-2.11
The higher the number of design changes required, the lower the probability of success of the NPD effort.	30	172	4	2423.6	-2.62
The company has adequate planning in the early stages of the NPD process.	31	90	4	2294.6	-2.66
Products or services developed in NPD consistently offer a competitive advantage in the marketplace regarding the schedule.	32	172	3	2388.3	-2.92
The organization quantifies product or service failure modes throughout NPD.	33	188	4	2394.8	-3
The NPD project has stable requirements and specifications that are maintained throughout the development process.	34	90	3	2148	-3.55
The NPD team thoroughly applies the NPD process and tools to their fullest extent.	35	162	3	2233.8	-4.1
NPD projects have realistic and stable project schedules.	36	90	3	2000.1	-4.45

3.6 Conduct Factor Analysis

Using principal components extraction and Varimax rotation, factor analysis grouped the top-ranked CSFs. Principal components extraction was chosen because the data were non-normally distributed, following best practices outlined by Costello and Osborne (2005). Varimax rotation was selected to achieve a clearer, more interpretable factor structure, as recommended by Goldberg and Velicer (2006). A minimum factor loading threshold of 0.32 was initially used, later adjusted to 0.24 to ensure sufficient grouping. This analysis resulted in two main groupings: front-to-end execution factors and supporting elements (Table 8).

Table 8. Factor Analysis Grouping Results

<table>
<tr><th colspan="3">Front-to-End Execution</th></tr>
<tr><td rowspan="6">Inputs</td><td rowspan="2">Voice of the Customer</td><td>The NPD team gathers the voice of the customer (i.e., needs, wants, and problems).</td></tr>
<tr><td>The NPD team uses the voice of the customer to define and develop the product or service throughout the NPD process.</td></tr>
<tr><td>Competition Benchmarking</td><td>The organization benchmarks the competition during NPD (i.e., products, pricing, and strategies).</td></tr>
<tr><td>Supply Base Experience</td><td>The NPD team considers the supply base’s knowledge and experience with the technology.</td></tr>
<tr><td>Requirements</td><td>The NPD project has clearly defined requirements and specifications.</td></tr>
<tr style="display:none"></tr>
<tr><td rowspan="2">Robust Methods</td><td>Design</td><td>The NPD team focuses on robust design methods in the product or process.</td></tr>
<tr><td>Manufacture Assembly</td><td>The NPD team focuses on robust manufacturing and assembly methods of products or service delivery.</td></tr>
<tr><td rowspan="2">Outputs</td><td>Superior Quality</td><td>The NPD team focuses on superior quality in the product or process.</td></tr>
<tr><td>Performance</td><td>Products or services developed in the NPD consistently offer a competitive advantage in the marketplace in terms of performance.</td></tr>
<tr><th colspan="3">Supporting Elements</th></tr>
<tr><td rowspan="5">Supporting Elements</td><td>NPD Execution Processes</td><td>NPD documentation includes stage/gate criteria and deliverables.</td></tr>
<tr><td rowspan="2">Leadership Engagement</td><td>The management team clearly drives the NPD effort’s scope, expectations, and value proposition.</td></tr>
<tr><td>Leadership/management is fully engaged in the NPD project.</td></tr>
<tr><td>Empowerment</td><td>Company culture creates an environment where the NPD project team feels empowered to execute the NPD project effectively and efficiently.</td></tr>
<tr><td>Accountability</td><td>The NPD team is accountable for the project’s success.</td></tr>
</table>

	Organizational Experience	The organization has documented design processes for its products or services.
		The organization has sufficient knowledge and experience in research and development.
		The organization has sufficient knowledge and experience in validation testing.

3.7 Report Results

The study grouped the top 17 CSFs into these two categories, providing a high-level conceptual framework for future NPD success strategies (Figure 8).

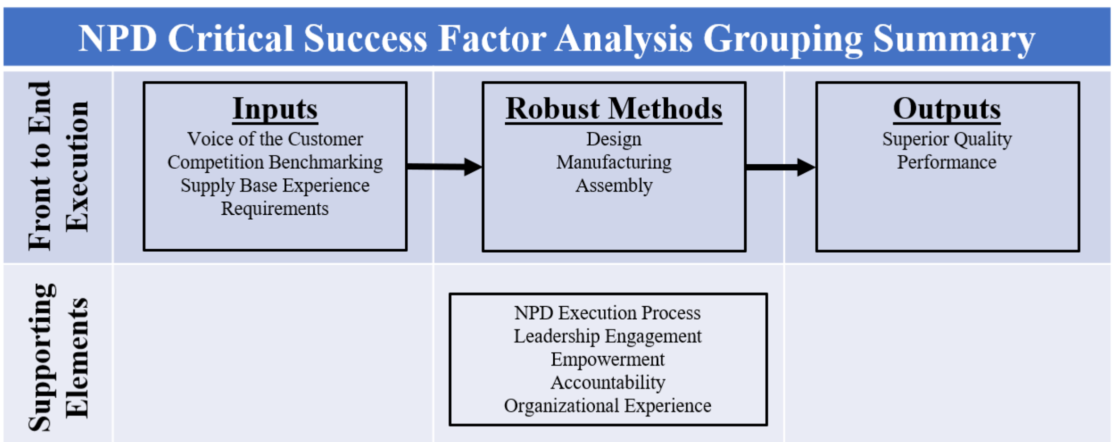

Figure 8. A High-Level Conceptual View of the Factor Analysis

4. Results and Discussion

4.1 Demographic Analysis

The demographic analysis of survey participants showed that 40.3% had participated in more than 11 NPD projects, and 63.5% had over 11 years of industry experience (Tables 2 and 3). These findings suggest that the survey responses reflect experienced professionals' insights. Additionally, 79.9% of respondents reported working for companies with a documented NPD process, closely aligning with Cooper et al.'s (2004c) finding that 73.7% of companies have such a process.

Figures 3 and 4 show survey respondents distributed across multiple industries and functional areas. Top industries included pharmaceuticals (18.8%), automotive (18.5%), engineering services (12.3%), and aerospace (5.5%). Product engineering (42.2%) and quality (18.8%) represented the most functional areas. In addition, respondents came from six continents, as shown in Figure 5, with the largest proportions from North America (43.9%), Asia (26.8%), and Europe (19.7%).

Company characteristics further revealed that 52.2% of respondents' companies had more than 1,000 employees, and 57.4% reported annual revenues over $10 million. Regarding R&D

investment, 33.8% worked for companies investing over 10% of sales in R&D (Tables 4, 5, and 6).

4.2 Survey Data Statistical Analysis

The Likert-scale data showed a slight right skew, and a central tendency around "agree" (scale point 4). The normality test (Figure 6) indicated non-normal distribution ($p < 0.005$), while the Multiple Comparisons test for equal variances (Figure 7) yielded $p = 0.087$, supporting equal variances. Given non-normality and equal variances, the Kruskal-Wallis non-parametric test was selected (Ruxton & Beauchamp, 2008).

4.3 Critical Success Factor Rankings

The Kruskal-Wallis analysis ranked CSFs based on survey responses (Table 7). Seventeen CSFs exhibited positive z-scores, indicating above-average importance. Figure 9 shows the cumulative Likert scale responses, organized by CSF rank.

The highest-ranked CSFs emphasized the importance of a documented NPD process with stage/gate criteria, robust design methods, customer requirements (VOC), benchmarking competition, and leadership engagement. Supporting organizational factors, such as supplier knowledge integration, R&D experience, and quality focus, are also ranked highly.

Figure 9. CSF Response Rate for Each Likert Scale Level

4.4 Factor Analysis and Grouping of CSFs

Factor analysis was conducted using principal components extraction and Varimax rotation to group related CSFs. The loading threshold was set at 0.32 and later adjusted to 0.24 for sufficient grouping. The resulting two major groupings were front-to-end execution and supporting elements. Front-to-end execution encompasses the executional flow from initial customer and business requirements to superior product quality and performance. Supporting elements encompass leadership engagement, empowerment, accountability, and organizational experience and knowledge (Table 8, Figure 9).

In addition to gathering early requirements and ensuring supplier engagement, NPD teams must apply robust design principles to deliver reliable outputs. Mashhadi et al. (2012) emphasized the importance of robust design in increasing customer value and reducing variability in NPD outcomes. Team leadership and learning also play critical roles. Sarin and McDermott (2003) found that cross-functional team performance improves significantly when leaders foster knowledge sharing and learning behaviors, which directly supports project innovation and speed to market. This two-part framework aligns with the concept that organizational and leadership support must complement strong front-end processes throughout the NPD life cycle.

5. Conclusions, Limitations, and Future Research

This study investigated the CSFs for NPD through a worldwide multi-industry survey. The analysis, supported by experienced respondents across industries and continents, identified the most influential CSFs that drive NPD project success. Seventeen critical success factors were statistically above average based on the Kruskal-Wallis non-parametric analysis. These factors were organized through factor analysis into two primary groups: Front-to-End Execution and Supporting Elements. Front-to-End Execution emphasizes the importance of robust methods, clear customer and business requirements, benchmarking, supplier knowledge, and ensuring quality and performance outputs. Supporting Elements highlight the necessity of leadership engagement, empowerment, accountability, and a strong organizational experience and knowledge foundation. This framework offers important guidance for industry leaders seeking to build or refine their NPD structures, methods, and processes. A clear focus on executional rigor and leadership-driven support can significantly enhance new product success and, by extension, a company’s competitive positioning and sustainability.

Future research should extend this work by developing a practical methodology or framework for risk mitigation and best practices in NPD execution based on the identified CSFs. Additionally, researchers should explore how these factors vary across different industries, company sizes, and global regions, particularly in underrepresented sectors and geographies. Validation studies using longitudinal datasets could also enhance the generalizability of the findings.

Several limitations must be acknowledged. The survey was administered in three phases, leading to sample differences across distribution waves. While all sample sizes were statistically sufficient, future work should use a single, unified survey instrument to strengthen consistency. Additionally, the literature review focused exclusively on peer-reviewed, English-language journal articles; expanding the review to include books, dissertations, and non-English sources may reveal additional success factors. Despite these limitations, the findings provide a valuable and actionable contribution to understanding how organizations can enable successful new product development efforts.

6. Disclaimer Statements

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SURVEYING BARRIERS TO STEM HIGHER EDUCATION FOR LOW-INCOME HIGH SCHOOL STUDENTS

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Abstract

This study examines how limited STEM resources in underfunded northern Ohio high schools restrict low-income students' access to laboratories, hands-on learning, and advanced coursework. Using survey data collected from high school students, the findings show that opportunity gaps, rather than ability, drive disparities in STEM preparedness. While a large majority of students express strong interest in STEM, only a small percentage report consistent access to hands-on and lab-based learning. These gaps hinder skill development and create systemic barriers to pursuing STEM degrees and higher-education opportunities. This paper also identifies strategies to increase high school students' interest and engagement in STEM.

Keywords: *STEM Education; Opportunity Gap; STEM Equity; Low-Income Students; Underfunded Schools; Hands-On Learning*

1. Introduction

STEM education plays an important role in shaping a student's future, including their career path, economic mobility, and overall readiness. However, access to STEM resources and opportunities is not equally distributed. Many underfunded high schools, which often serve a large population of low-income and minority students, lack qualified STEM teachers, laboratory spaces, and updated course materials (Banilower et al., 2018). Because of this, students' academic and career choices after high school are influenced less by their ability and more by the limitations of their environment. As opposed to previous studies that emphasized the importance of teachers' feedback at the school level, this study is more interested in the perspectives of students and thus provides a student-centered view on the impediments to STEM involvement.

According to the U.S. Department of Education's Office for Civil Rights, students in high-poverty schools are less likely to have access to advanced courses such as calculus, physics, and computer science (U.S. Department of Education, Office for Civil Rights, 2021). These courses are important for preparing students for college and STEM careers (National Academy of Engineering, 2010). When students do not have access to these opportunities, they are less likely to develop the skills needed to succeed in these fields. Despite these barriers, many students still show strong interest in STEM, especially in hands-on and real-world learning experiences. The issue is not a lack of motivation, but a lack of opportunity.

To better understand these challenges, this study uses survey data collected from low-income high school students in underfunded schools in northern Ohio to capture their experiences, perceptions, and access to STEM learning opportunities.

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This study focuses on how opportunity gaps in underfunded high schools affect how students view STEM, college, and their future career paths. It also explores how these limitations impact students' confidence and preparedness for STEM fields. The goal of this study is not only to highlight these barriers but also to better understand students' experiences and identify ways to improve access to STEM opportunities.

2. Literature Review

Research shows that there are major differences in access to STEM education across schools with different socioeconomic backgrounds. Data from the U.S. Department of Education's Civil Rights Data Collection shows that high-poverty schools are less likely to offer advanced courses such as calculus, physics, and computer science (U.S. Department of Education, Office for Civil Rights, 2021). These courses are important for students who want to pursue STEM majors and careers after high school (National Academy of Engineering, 2010). When schools do not offer these courses, students have fewer opportunities to prepare for college and limit their future career options.

Studies from Georgetown University have shown that STEM majors are linked to higher salaries, lower unemployment rates, and more stable careers (Georgetown University Center on Education and the Workforce, 2015; 2018). Additional data from the U.S. Bureau of Labor Statistics also supports the strong demand and long-term benefits of STEM careers (U.S. Bureau of Labor Statistics, 2024). These benefits highlight how important STEM education is for improving economic mobility, especially for low-income students. However, students who do not have access to strong STEM education in high school often struggle later because they lack the foundation needed to succeed in college-level STEM courses.

Many studies agree that these gaps are not caused by differences in student ability, but by differences in resources and opportunities (National Science Foundation, 2019). However, most of this research focuses on data from schools or teachers rather than the students themselves. Because of this, there is limited understanding of how students personally experience these challenges. Despite the existence of numerous previous studies on STEM inequality that were carried out from the points of view of schools, teachers, and institutions, very few considered the point of view of the students affected by STEM inequality. This study aims to analyze how being deprived of access to STEM materials influences the interest, self-confidence, and career objectives of these students attending those inadequately financed high schools in northern Ohio.

This study helps fill that gap by focusing on student survey data to better understand how limited access to STEM resources affects their interest, confidence, and future goals in STEM.

The study will be based on the hypothesis; equal capabilities do not mean provision of equal educational opportunities. Students in institutions that receive insufficient funding lack many opportunities in the field of science and technology that could influence their preparation and possible future career choices. It is vital to gain knowledge on this issue from the perspective of the students themselves.

3. Methodology

Data was collected using a structured survey consisting of multiple-choice questions and one open-ended response. The survey was designed to capture students' experiences with STEM education, including access to technology, laboratory resources, coursework, hands-on learning opportunities, and overall interest in STEM fields. The survey questions were developed based on the objectives of this study and were informed by prior research highlighting the importance of laboratory access, advanced coursework, hands-on learning, and student perceptions in shaping STEM participation (Banilower et al., 2018; U.S. Department of Education, Office for Civil Rights, 2021). The questions were written in clear and simple language to ensure they were easily understood by high school students. Table 1 summarizes the survey questions and corresponding variables used to assess students' access to STEM resources, learning experiences, and career interests.

Table 1. Survey Instrument and Measured Variables

	Survey Question	Response Type	Variable Measured
1	What grade are you currently in?	Open-ended	Demographics (Grade Level)
2	How would you describe your school's access to technology and science equipment?	Likert (Excellent–Poor)	Resource Availability
3	Have you ever taken a STEM-related course?	Yes/No	STEM Exposure
4	Are there STEM clubs, competitions, or after-school programs available at your school?	Multiple Choice	Extracurricular Access
5	Which STEM subject do you enjoy the most?	Multiple Choice	STEM Interest
6	What makes you interested in STEM subjects?	Multiple Choice	Motivation Factors
7	Do you believe STEM skills are important for your future career?	Likert Scale	Perceived Value of STEM
8	What makes STEM subjects hard or less interesting?	Multiple Choice	Barriers to Engagement
9	Does your school provide enough hands-on activities (labs/projects)?	Likert Scale	Hands-on Learning Access
10	Do you have access to a science or computer lab?	Multiple Choice	Lab Access
11	How often do teachers use real-world examples in STEM lessons?	Likert Scale	Instructional Quality
12	Does your family encourage you to explore STEM?	Likert Scale	Family Support
13	Have you ever thought STEM is "too hard" or "not for me"?	Multiple Choice	Self-Perception
14	Have you visited a science fair, museum, or STEM-related company?	Multiple Choice	Exposure to STEM Environments
15	How often does your school organize STEM events or competitions?	Multiple Choice	Institutional Support
16	Do you see yourself in a STEM career in the future?	Multiple Choice	Career Intent
17	What do you want to be when you grow up?	Open-ended	Career Aspiration

Participants were high school students attending underfunded schools in northern Ohio that primarily serve low-income communities. The survey included questions related to access to STEM courses, availability of labs and equipment, participation in STEM activities, and perceptions of preparedness for college-level STEM coursework. A total of 45 responses were collected. Participants were selected based on their enrollment in under-resourced schools and their exposure to limited STEM opportunities. All responses were collected anonymously, and no personally identifiable information was recorded to ensure confidentiality.

The survey tool was constructed using the objectives of the present study and drawing on the relevant literature pertaining to STEM education, educational equity, and access to STEM. The questions contained in the survey were aimed at examining the students' experience with lab access, STEM courses, hands-on experience, extra-curricular activities, and attitudes toward STEM careers. Since the present study is exploratory in nature, no statistical validation of the survey tool was performed. Nonetheless, the survey tool was constructed with respect to the objectives of the present study and literature.

4. Data Analysis and Results

After completing the school visits and survey collection, all responses were compiled and analyzed. Multiple-choice responses were coded and analyzed using descriptive statistics, including frequencies and percentages, to identify patterns in STEM resource access (21.3%).

TEM resource access, hands-on learning availability, and student perceptions. Descriptive comparisons were also used to examine relationships between access to STEM resources and students' interest and career intentions. Open-ended responses were reviewed and grouped into common themes to better understand students' career interests and concerns related to STEM pathways. The analysis focused on identifying patterns in access, interest, and perceived barriers across the sample.

Figure 1 summarizes the key findings from the survey, including students' access to STEM resources, participation in STEM activities, and overall perceptions of STEM education.

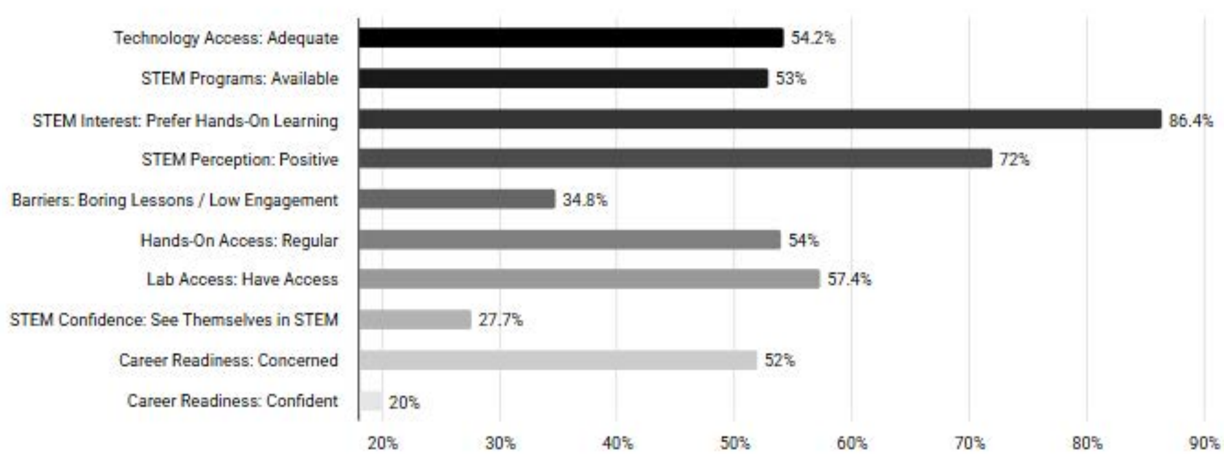

Figure 1. Summary of Survey Results

Regarding access to technology, 54.2% of students reported adequate access, while 45.8% reported limited access. This indicates that access to essential STEM resources is present but remains uneven across students.

In terms of STEM exposure, 73.9% of students reported participating in at least one STEM-related activity. However, access to structured STEM programs is limited. 53% of students indicated that their schools offer active STEM programs, while 47% reported access to two or fewer programs.

Student interest in STEM remains high, with 86.4% identifying hands-on projects as the most engaging factor in learning. Despite this strong interest, opportunities to engage in practical learning are limited, with 46% of students reporting consistent access to real-world applications.

In terms of perception, 72% of students agreed that STEM careers offer high rewards, while 28% reported uncertainty about associated risks. Several barriers to engagement were identified, including lack of resources (24%), the perception that STEM is “not for them” (12%), and occasional disconnection from STEM reported by more than 40% of students.

Looking at the outlook, only 27.7% of students reported that they see themselves pursuing a STEM career, while 72% expressed uncertainty about their future. School-based STEM opportunities were also reported as infrequent, with 40-45% of students indicating that opportunities occur rarely or never occur.

52% of students reported concern about pursuing STEM careers, while only 20% reported confidence in doing so. These findings highlight a gap between student interest in STEM and their confidence in pursuing STEM pathways.

5. Discussion: Barriers Identified

The findings show that a major reason why students at under-resourced schools struggle with science and engineering is not because they lack will or ability, but because there are gaps in their opportunities. While students have a strong desire to pursue science and engineering, especially hands-on learning, they often do not have access to labs, organized programs, or advanced courses. This aligns with findings by Spivak et al. (2025), who showed that hands-on tools such as 3D printing enhance student engagement and comprehension in STEM learning environments. This creates an “opportunity gap” that adds stress to their experiences and limits their path toward STEM fields. At the national level, similar patterns are observed, as achievement gaps exist in high-poverty districts, with test scores in cities like Detroit, Cleveland, and Baltimore below the national average (National Center for Education Statistics, 2023).

Beyond limited instructional resources, students also have fewer opportunities to take advanced courses and often feel more uncertain about college preparedness. Many responses reflected concerns about financial risk and fear of failure in both academics and future careers. Overall, the issue is opportunity rather than a lack of skill or motivation. Strategies such as near-peer mentoring, low-cost hands-on activities, and STEM clubs can help address this gap. Mentoring has been shown to improve confidence and persistence (National Science Foundation, 2019), while hands-on learning and informal programs increase engagement and interest (National Academy of Engineering, 2010; Banilower et al., 2018). Increasing awareness of STEM career benefits can also motivate students to pursue these fields (Georgetown University Center on Education and the Workforce, 2015).

6. Practical Strategies to Enhance STEM Engagement

The study and existing literature suggest that low-income students are interested in STEM but require structured support to overcome barriers (RAND Corporation, 2018). In resource-limited schools, low-cost and scalable strategies can significantly improve student engagement and persistence (National Academy of Engineering, 2010).

One effective approach is the use of low-cost near-peer mentoring, such as tutoring or advising from college students, recent graduates, or advanced high school students. These programs, often offered through after-school activities or clubs, provide relatable role models and support without requiring additional teachers or high costs. Research shows that mentoring improves self-efficacy and persistence among underrepresented students in STEM (National Science Foundation, 2019).

For students with limited access to laboratories, low-cost hands-on engineering activities are essential. Using simple materials, simulations, or virtual tools, students can develop problem-solving skills and engage in design-based learning even in low-resource environments (National Academy of Engineering, 2010).

Participation in STEM clubs and informal learning programs is also critical, particularly when advanced coursework is unavailable. These activities provide opportunities for hands-on learning, collaboration, and continued exposure to STEM concepts. Informal STEM participation has been shown to improve engagement, STEM identity, and the likelihood of pursuing STEM education (Banilower et al., 2018; National Science Foundation, 2019). Programs such as Science Olympiad and FIRST Robotics demonstrate these benefits, though similar outcomes can be achieved through lower-cost alternatives (FIRST Robotics, 2020).

Career awareness also plays an important role. STEM careers offer strong earning potential and job security, which can motivate students, especially in low-income settings (Georgetown University Center on Education and the Workforce, 2015). Encouraging a positive mindset toward learning challenges, along with the use of free online resources such as Khan Academy, can further support student confidence and preparation for STEM pathways.

7. Conclusion and Recommendations

The present study indicates that unequal opportunities, rather than unequal ability in STEM learning environments, exist in schools today. The lack of access to hands-on experiences, laboratory-based science courses, AP and advanced classes, and a rigorous sequence of coursework contributes to these inequalities (RAND Corporation, 2018). Although students demonstrate strong interest and awareness of STEM careers, they often do not receive the opportunities needed for hands-on learning or preparation for rigorous STEM coursework (National Academy of Engineering, 2010). Interventions are necessary to address these gaps without stigmatizing students or creating pathways for failure (National Science Foundation, 2019).

Low-cost engineering design challenges, peer mentoring, student-run clubs, informal after-school STEM programs, career conversations, and access to low-cost online courses are all effective interventions (National Science Foundation, 2019). In addition, there is a need for broader systemic change, including advocacy among educators, school administrators, and policymakers at local, state, and national levels. Efforts should focus on strengthening school-community partnerships, improving the distribution of resources, and increasing the value placed on learning and opportunity (U.S. Department of Education Office for Civil Rights, 2018).

Overall, integrating research with practical interventions in low-resource schools can improve students' academic preparation and support their long-term career development in STEM fields.

Future research should examine STEM interest and engagement at earlier education levels to better understand when student confidence, interest, and perceived barriers begin to develop. In addition, future work should evaluate the effectiveness of low-cost interventions, such as mentoring and hands-on activities, and explore the use of technology-based solutions, such as virtual labs, to expand access to STEM opportunities in under-resourced schools.

8. Disclaimer Statements

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ENGINEERING AND MANAGEMENT INTEGRATION IN THE CLASSROOM: USING FRAMEWORKS TO DEVELOP SYSTEMS THINKING AND MORE COMPREHENSIVE SOLUTION-FINDING

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Abstract

Engineering education has historically emphasized technical problem-solving, often at the expense of broader contextual understanding. However, contemporary engineering challenges, particularly in energy systems, are inherently complex socio-technical problems that require integrating social, political, economic, environmental, and technological considerations. This study introduced a modified form of PESTLE analysis as a structured pedagogical tool to promote systems-level thinking in undergraduate engineering education. A classroom intervention incorporating this framework alongside complementary constructs – Corporate Social Responsibility (CSR); Environmental, Social, and Governance (ESG); and the Triple Bottom Line (TBL) – was implemented through energy-focused case studies. Pre- and post-assessments were analyzed using qualitative thematic coding to evaluate shifts in student reasoning. The results indicated a clear transition from simplified, moralistic explanations to more integrated, constraint-aware, and implementation-focused analyses. Students demonstrated improved recognition of policy, economic, and infrastructural constraints as well as enhanced systems-oriented reasoning. These findings suggest that integrating framework-based approaches with systems thinking strengthens interdisciplinary competence and supports more effective decision-making in complex engineering contexts.

Keywords: *Systems Thinking; Engineering Education; PESTEL; Sustainability; Energy Systems; Decision-Making; Framework Thinking*

1. Introduction

Engineering education has traditionally emphasized technical rigor and analytical problem-solving as core competencies. While these skills are essential, this approach often leaves students underprepared for the realities of contemporary engineering practice, where challenges are characterized by uncertainty, competing constraints, and interdisciplinary complexity. Engineers must increasingly operate within systems that extend beyond purely technical domains, requiring engagement with economic pressure, regulatory frameworks, environmental considerations, and societal expectations. As a result, there is growing recognition of the need to integrate better systems thinking and contextual awareness into undergraduate engineering curricula.

Energy systems provide a particularly salient context for addressing this gap. The design and implementation of energy solutions require not only technical feasibility, but also economic viability, policy alignment, environmental sustainability, and social acceptance. However, engineering students are often primarily trained to develop technically optimal solutions, without sufficiently

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considering these broader dimensions. This can limit their ability to evaluate trade-offs, anticipate constraints, or design implementable solutions in real-world contexts. Structured frameworks that explicitly incorporate multiple dimensions of analysis may therefore play a critical role in supporting more comprehensive and realistic problem-solving.

The PESTLE framework offers a well-established approach for analyzing macro-environmental factors; however, its application in engineering education remains limited. To address this gap, this study introduces a simplified version of PESTLE – encompassing technology, the environment, society, politics, and economics – and investigates its effectiveness as a pedagogical tool for fostering system-level thinking among undergraduate engineering students. By embedding this framework in energy-focused case studies, this study evaluates how structured, interdisciplinary analysis influences students' reasoning and their ability to engage with complex socio-technical challenges.

2. Literature Review and Background

2.1. The Need for Systems Thinking in Engineering Education

Engineering education has traditionally emphasized technical rigor and analytical problem-solving, often focusing on well-structured problems with clear solutions. While this approach builds foundational competencies, it does not adequately prepare students for contemporary engineering challenges, which are characterized by uncertainty, interdependence, and competing constraints (Nagarajan & Overton, 2019; Lönngren & Svanström, 2016). These challenges, particularly in domains such as energy and sustainability, are inherently socio-technical and require integrating technological, environmental, economic, political, and social considerations (Voulvoulis et al., 2022).

Systems thinking has emerged as a critical competency of modern engineers. This involves understanding the relationships among system components, identifying feedback loops, and recognizing how interactions produce emergent outcomes across domains (Peretz, 2025; Nagarajan & Overton, 2019). In sustainability contexts, systems thinking also requires attention to multiple scales and anticipation of unintended consequences (Lönngren & Svanström, 2016). Despite its recognized importance, implementation remains fragmented and often limited to isolated modules rather than integrated curricula (Raspini et al., 2025; Sabri, 2025). This gap highlights the need for pedagogical approaches that support integrative system-level reasoning (Alhassani et al., 2025; Thian et al., 2026).

2.2. Wicked Problems and Socio-Technical Complexity

Many contemporary engineering challenges are best understood as "wicked problems," characterized by complexity, uncertainty, and competing stakeholder interests (Lönngren & Svanström, 2016). In sustainability and energy contexts, these challenges involve tightly coupled socio-technical systems in which infrastructure, policy, economics, and human behavior interact dynamically. Traditional approaches that optimize within isolated subsystems are insufficient because they fail to capture trade-offs, value conflicts, and system-wide feedback (Souliotis & Voulvoulis, 2025; Voulvoulis et al., 2022).

Students often struggle to engage with such complexity, tending to oversimplify problems into linear cause–and–effect relationships or to rely on moralistic explanations rather than integrated analysis. This underscores the need for instructional approaches that provide both conceptual understanding and structured tools to support the navigation of complex systems.

2.3. Pedagogical Approaches and the Need for Structure

Active learning approaches, such as project-based learning (PjBL) and problem-based learning (PBL), are widely used to promote systems thinking. These methods engage students in real-world problems, fostering interdisciplinary inquiry, collaboration, and critical thinking (Nagarajan & Overton, 2019; d'Escoffier et al., 2024). Research demonstrates that such approaches improve students' ability to identify system components and analyze interconnections across sustainability domains (Ekselsa et al., 2023; Esquicha-Tejada et al., 2026).

However, these pedagogies often lack analytical support. Systems thinking can be abstract and difficult for students to apply, and many lack tools to operationalize it in complex problem contexts (Peretz, 2025; Raspini et al., 2025). Consequently, student analyses may remain incomplete or disproportionately focused on familiar domains. This limitation highlights the importance of a structured approach that can guide comprehensive reasoning.

2.4. Framework-Based Approaches and Cognitive Scaffolding

Framework-based approaches provide structured methods for organizing complex problems and can be understood as a form of "framework thinking." In sustainability education, frameworks such as Triple Bottom Line (TBL); Corporate Social Responsibility (CSR); and Environmental, Social, and Governance (ESG) extend analysis to include environmental and social dimensions alongside economic performance (Alhassani et al., 2025; Gutierrez-Bucheli et al., 2022).

These frameworks serve as cognitive scaffolds by reducing the cognitive load and enabling students to systematically decompose complex systems while maintaining awareness of multiple interacting factors. By organizing problem spaces into defined categories, frameworks help students avoid being overwhelmed and support more consistent multidisciplinary analysis.

The PESTLE framework, which encompasses political, economic, social, technological, legal, and environmental dimensions, is particularly relevant. Originally used in strategic management, PESTLE was adapted to support multidisciplinary analysis in engineering education (Casañ et al., 2021). Studies have shown that PESTLE-based activities improve students' ability to identify trade-offs, recognize interdependencies, and engage with sustainability challenges from multiple perspectives (Casañ et al., 2021). However, PESTLE is inherently static and does not explicitly capture system dynamics such as feedback loops or temporal changes.

2.5. Integrating Systems Thinking and Framework Thinking

Systems and framework thinking are complementary approaches. Systems thinking emphasizes relationships, feedback loops, and dynamic system behavior, whereas framework thinking emphasizes structured categorization and domain coverage. Each addresses the limitations of the other: systems thinking provides depth but can be abstract, whereas frameworks provide clarity but may lack a dynamic perspective.

Integrating these approaches offers a more complete analytical toolkit by supporting both relational reasoning and structured decomposition (Azad & Moore, 2024). This integration is particularly valuable in energy systems, where students must evaluate trade-offs (e.g., cost, emissions, and equity) while also understanding feedback mechanisms such as policy incentives that shape technology adoption (Cole et al., 2025). Combining structured frameworks with systems thinking allows students to organize complex information and interpret system behavior within real-world constraints.

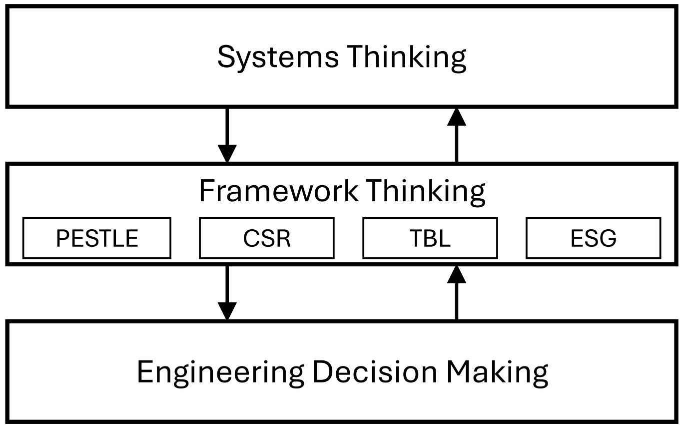

Figure 1. Conceptual Integration of Intervention

Figure 1 illustrates the conceptual relationship among the analytical frameworks incorporated in this study. Systems thinking serves as the overarching perspective through which students examine complex socio-technical systems. At the same time, PESTLE, CSR, ESG, and TBL provide complementary structures for organizing and evaluating technological, environmental, social, political, and economic considerations. Together, these approaches offer a scaffolded process for understanding interdependencies, identifying trade-offs, and evaluating engineering decisions within broader and more abstract societal contexts.

2.6. Synthesis and Research Gap

Literature demonstrates that systems thinking is essential for addressing complex engineering challenges, particularly in sustainability and energy contexts (Nagarajan & Overton, 2019; Thian et al., 2026). Active learning approaches effectively engage students but often lack the structure needed for comprehensive analysis, whereas frameworks provide valuable scaffolding but may overlook system dynamics.

Despite their complementary strengths, however, these approaches have rarely been integrated. Students often lack tools to translate abstract systems thinking into structured analytical processes, leading to simplified or fragmented reasoning. Furthermore, few studies have examined how combining these approaches influences student understanding, particularly in energy-focused contexts.

This study addresses this gap by adopting a hybrid pedagogical approach that integrates systems thinking with a modified PESTLE framework and complementary sustainability constructs (CSR, ESG, and TBL). By embedding this approach in energy-focused case studies, this research investigates how structured analytical scaffolding can support systems-level reasoning, enhance the understanding of trade-offs, and promote more implementation-focused analysis of complex socio-technical systems.

3. Methodology

This study employed a classroom-based intervention design to evaluate the framework's effectiveness in promoting systems-level thinking among undergraduate engineering students. A summary of the study phases is shown in Table 1. The intervention was implemented within a single undergraduate engineering economics course at University of Portland during the Spring 2025 semester and was integrated into existing instructional activities. A total of 25 students participated in the study, and most were junior-level engineering majors. Participation in the instructional activities was part of normal course requirements, and survey responses were collected and analyzed in accordance with institutional guidelines.

Table 1. Study And Intervention Phases

Phase	Activity
Pre-Assessment	Survey on energy challenges, causes, and barriers
Instruction	Systems thinking, PESTLE, CSR, ESG, TBL concepts
Guided case	Wind energy repowering analysis
Group cases	Transmission corridor and solar agriculture cases
Post-assessment	Repeat pre-assessment survey
Analysis	Thematic coding and comparison

Students were introduced to the most relevant factors (technology, environment, society, politics, and economics) alongside complementary management-oriented concepts, including TBL, CSR, and ESG frameworks. These concepts were presented sequentially to establish a foundation for understanding the broader sociotechnical context of engineering decision-making.

Following this conceptual introduction, students were exposed to the fundamental aspects of energy systems, including energy generation, distribution, consumption, and associated environmental and waste considerations. The instruction then transitioned to applied learning through case-based activities. The instructor first facilitated a whole-class guided analysis of a wind energy repowering case study, modeling the application of a PESTLE-informed approach. Subsequently, the students worked in small groups to analyze one of the two additional energy-focused case studies. The first case examined tensions between environmental conservation and the need for transmission infrastructure development across protected natural land, highlighting conflicts between the public interest, ecological preservation, utility rights, and energy demands. The second case explored the trade-offs associated with converting agricultural land for solar energy production, emphasizing the competing priorities among food production, land use, renewable energy expansion, and rural economic development. These activities were designed to encourage students to apply the framework to structured interdisciplinary analyses.

To assess the impact of the intervention, students completed a pre- and post-intervention survey comprising quantitative and qualitative components; however, the present study focuses on qualitative findings because the primary objective was to evaluate shifts in student reasoning and systems-level thinking. The survey instrument included Likert-scale items that measured perceptions of the importance of energy challenges and interest in pursuing energy-related careers. In addition, open-ended questions prompted students to articulate their understanding of the "energy problem," identify its underlying causes, and describe the perceived barriers to its resolution.

Qualitative responses were analyzed using a thematic coding approach to identify patterns and shifts in conceptual understanding over time. Responses from the pre- and post-intervention surveys were reviewed and coded for recurring concepts across technological, environmental, social, political, and economic domains. Initial codes were iteratively refined into broader thematic categories that captured common patterns in student reasoning. Particular attention was given to changes in the breadth, depth, and integration of the factors considered, as well as evidence of systems-oriented thinking and recognition of system interdependencies. Representative themes were then compared across the pre- and post-intervention datasets to identify shifts in conceptual understanding. This mixed-methods approach enabled the study to capture both attitudinal changes and the evolution of systems-level reasoning resulting from the intervention.

4. Results and Findings

The quantitative results from the survey were not statistically significant. Instead, the results will focus on qualitative findings because insights into shifts in student reasoning and systems-level thinking will improve future instruction.

4.1. Conceptualization of the Energy Problem

Analysis of student responses to the open-ended question, “What is the energy problem?”, revealed a clear shift in both the depth and structure of students’ understanding following the intervention. Themes are summarized in Table 2. Before the intervention, the responses were primarily broad, intuitive descriptions emphasizing resource scarcity and environmental harm. Many students framed the energy problem as the depletion of finite fossil fuels or the growing imbalance between supply and demand, often expressed in simplified terms such as “running out of energy” or “infinite want and finite resources.” While environmental concerns, including pollution and climate change, were frequently mentioned, these references tended to be descriptive rather than analytical, with limited discussion of the underlying causes, constraints, or trade-offs. Additionally, a few responses addressed infrastructure, economics, or policy, and some were vague or conceptually underdeveloped.

Table 2. Summarized Energy Problem Themes

Theme	Pre-Intervention	Post-Intervention
Resource scarcity	High	Moderate
Environmental impacts	High	High
Infrastructure constraints	Low	High
Regulatory barriers	Low	High
Economic trade-offs	Low	High
Equity/access concerns	Absent	Moderate
Renewable transition complexity	Low	High

Following the intervention, the students’ responses demonstrated a marked transition toward more integrated and systems-oriented reasoning. Rather than focusing narrowly on scarcity or environmental impact, students increasingly defined the energy problem as a multidimensional challenge that requires balancing the rising demand with sustainability, affordability, and feasibility. For example, many responses explicitly referenced economic, infrastructure, and regulatory barriers, reflecting broader consideration of real-world constraints. Students also acknowledged the complexities of transitioning more frequently from fossil fuels to renewable energy, including challenges related to scalability, storage, and implementation. This shift indicates an improved recognition of the interconnected nature of technological, economic, and policy dimensions within energy systems.

Thematic coding further highlighted this progression. Before the intervention, the dominant themes included resource scarcity and environmental impacts, with a limited representation of economic constraints, infrastructure considerations, and policy factors. Post-intervention responses showed a redistribution of themes, with substantial increases in sustainability-oriented framing; challenges in the renewable transition; and explicit references to economic, infrastructure, and regulatory constraints. Mentions of equity and access, absent in the pre-intervention responses, also became more prominent, indicating a broader understanding of the societal dimensions of energy systems.

Overall, these findings suggest that the intervention facilitated a shift from descriptive and single-factor explanations toward more analytical, constraint-aware, and system-level conceptualizations of the energy problem. Students not only expanded the range of factors considered but also demonstrated an increased ability to articulate the interdependencies and trade-offs inherent in complex socio-technical systems. This progression reflects meaningful development in systems thinking and aligns with the framework's intended outcomes and the associated instructional strategies.

4.2. Perceived Causes of the Energy Problem

Analysis of student responses to the question, “What are all the reasons you think the energy problem exists?”, revealed a substantive shift in how students conceptualized causality within energy systems. Themes are summarized in Table 3. Before the intervention, the responses were broad, fragmented, and frequently framed in terms of individual behavior or moral judgment. Many students emphasized factors such as greed, overconsumption, or general human behavior, often listing multiple causes without articulating clear relationships among them. While some responses referenced infrastructure limitations or fossil fuel dependence, these were typically expressed at a surface level, with limited attention paid to the systemic interactions among technological, economic, and political factors. Policy and regulatory considerations were mentioned infrequently, and several responses exhibited conceptual drift, including references unrelated to energy systems, indicating unclear boundaries.

Table 3. Summarized Themes of Causes of the Energy Problem and Barriers to Solutions

Theme	Pre-Intervention	Post-Intervention
Resource scarcity	High	Moderate
Environmental impacts	High	High
Infrastructure constraints	Low	High
Regulatory barriers	Low	High
Economic trade-offs	Low	High
Equity/access concerns	Absent	Moderate
Renewable transition complexity	Low	High

Following the intervention, student responses demonstrated a marked transition toward more structured, systems-oriented explanations of causality. Students increasingly articulated the energy problem as a set of interacting constraints, including fossil fuel dependence, inadequate infrastructure for renewable energy, political and regulatory barriers, economic incentives, and the growing demand driven by population growth and technological development. Rather than attributing the problem primarily to isolated factors or blame-oriented narratives, responses more frequently reflected cause-and-effect reasoning and acknowledged the complexity of the energy transitions. For example, students highlighted how policy incentives, economic costs, and social resistance collectively shaped the feasibility of adopting alternative energy systems.

The thematic analysis further underscores these shifts. Pre-intervention responses were dominated by themes related to demand growth and economic motivations (e.g., profit and greed), with moderate attention paid to infrastructure and fossil fuel dependence but limited engagement with policy and transition complexity. Post-intervention responses showed increased representation of policy and governance factors, as well as a substantial rise in references to transition-related constraints, such as cost, feasibility, and trade-offs. Notably, students also began to incorporate solution-oriented thinking, including references to renewable energy, efficiency improvements, and nuclear power, although the question did not explicitly ask for solutions. This suggests deeper engagement with the problem space and a growing ability to connect causes with potential forward pathways.

Overall, these findings indicate that the intervention supported a shift from intuitive, blame-focused explanations toward more analytical, systems-based reasoning regarding why the energy problem persists. Students demonstrated an increased ability to identify and integrate economic, political, technological, and social drivers as well as to recognize the interdependencies and trade-offs inherent in large-scale energy transitions. This progression reflects meaningful development in causal reasoning and aligns with the framework's goal of fostering systems-level understanding.

4.3. Perceived Barriers to Solving the Energy Problem

Analysis of student responses to the question, “What are all the barriers you can think of to solving the energy problem?” revealed a substantial shift in students' conceptualization of obstacles to energy system transformation. Table 3 (above) summarizes the response themes. Before the intervention, the responses were framed in moralistic and behavior-focused terms, emphasizing greed, apathy, political corruption, and individual unwillingness to change. Many students described barriers using abstract or normative language (e.g., “greed,” “people not caring,” “selfishness”), often without linking these ideas to specific mechanisms within energy systems. While political factors and economic concerns were frequently mentioned, they were typically expressed in general or vague terms, with little attention to how these forces interact with technological or infrastructural constraints. A smaller subset of responses cited technical issues, including battery limitations, grid capacity constraints, and transition challenges. However, these are inconsistent and are often embedded within broader, unstructured lists of concerns.

Following the intervention, students’ responses demonstrated a clear shift toward more analytical and systems-oriented reasoning. Barriers were increasingly framed as the result of interacting economic, technological, infrastructural, environmental, and policy constraints rather than solely as outcomes of individual or collective behavior. Students more frequently identified concrete challenges, such as high upfront costs, limited infrastructure for renewable energy, storage and intermittency issues, land and resource constraints, and regulatory complexities. In addition, the responses reflected greater awareness of environmental trade-offs, with students noting that energy solutions themselves, such as wind farms or transmission infrastructure, can introduce ecological and land-use conflicts. This indicates an increased recognition that potential solutions are embedded within competing priorities and constraints.

The thematic patterns further underscore this transition. Pre-intervention responses were dominated by moral and behavioral themes, with political and economic factors present but often loosely defined. Post-intervention responses showed a marked increase in references to economic (cost, funding), technological (infrastructure, storage, efficiency), and physical (land, materials) constraints, along with a stronger presence of system complexity, including difficulty achieving consensus and the absence of a single optimal solution. Although moral language did not disappear entirely, it played a less significant role within explanatory frameworks, suggesting a shift from blame-oriented reasoning to constraint-based analysis.

Overall, these findings indicate that the intervention supported meaningful progress in students' understanding of the barriers to solving complex socio-technical problems. Students moved from normative and generalized explanations to more detailed, multidimensional, and systems-informed perspectives. This shift reflects an enhanced ability to recognize trade-offs, interdependencies, and real-world implementation challenges, aligning with the framework's goal of fostering systems-level thinking.

5. Discussion

The results across all three qualitative questions (students' definitions of the energy problem, perceived causes, and perceived barriers) demonstrated a consistent and meaningful shift toward systems-level thinking following the intervention. Before the intervention, student responses to all prompts were characterized by generalized, often moralistic reasoning. Students frequently framed the energy problem in terms of resource scarcity, environmental harm, and individual or collective failures, such as greed or apathy. These perspectives, while not inaccurate, tended to be descriptive, fragmented, and to lack explicit connections among underlying causes, constraints, and implementation challenges.

Following the intervention, a clear pattern emerged across all three datasets. Students increasingly articulated the energy problem, its causes, and barriers in terms of interconnected socio-technical systems. In defining the energy problem (Question 1), the responses shifted from static notions of depletion and pollution to more dynamic formulations involving trade-offs among sustainability, demand, cost, and infrastructure. In identifying causes (Question 2), students moved from blame-oriented explanations to causal reasoning that incorporated economic incentives, policy constraints, technological limitations, and infrastructure dependencies. Similarly, in describing barriers (Question 3), responses evolved from moral and behavioral critiques to more concrete analyses of financial costs, regulatory complexity, technological limitations, and competing land use and environmental priorities. Across all three areas, students demonstrated an improved ability to articulate interconnected causes and barriers, including storage challenges, regulatory constraints, and transition costs, as well as greater recognition of environmental trade-offs and the absence of a single solution.

Taken together, these results indicate improved systems thinking as students shifted from simplistic, morality-based reasoning toward more structured, multi-factor analysis involving policy, economics, and infrastructure considerations. This progression suggests not only an expansion in the number of factors students consider but also an increase in the quality of reasoning, particularly in terms of identifying relationships, trade-offs, and constraints. Importantly, these changes reflect a shift toward more expert-like conceptualizations of complex engineering problems, in which solutions are understood as contingent, constrained, and context-dependent, rather than purely technical or idealized.

The observed shift toward multi-factor and constraint-aware reasoning is consistent with previous studies that found structured pedagogical approaches can strengthen systems thinking and sustainability competencies in engineering students (Nagarajan & Overton, 2019; Ekselsa et al., 2023). Similarly, Casañ et al. (2021) reported that PESTLE-based activities helped students identify connections across economic, environmental, and social dimensions. The present findings extend this work by demonstrating how a modified PESTLE framework, combined with CSR, ESG, and TBL concepts, can support systems-oriented reasoning in energy-focused engineering contexts.

These findings support the central premise of this study that integrating management-oriented frameworks into engineering education can enhance students' capacity for systems-level reasoning.

The framework provides a structured lens that bridges macro-level environmental analysis and engineering decision-making, enabling students to coherently organize and connect diverse considerations. By combining framework-based thinking with systems thinking, students developed more sophisticated, constraint-aware, and implementation-focused perspectives. This integration aligns with broader educational goals in engineering, including the development of interdisciplinary competence, sustainability awareness, and the ability to engage with real-world complexities. More broadly, the findings suggest that such approaches can help bridge the traditional divide between engineering and management disciplines by embedding socioeconomic and policy considerations directly into technical analysis.

Several limitations should be acknowledged when interpreting these findings. First, the study was conducted within a single undergraduate engineering course at one institution, which may limit the generalizability of the results to other educational contexts. Second, the sample reflected a specific student population and instructional setting. Third, the findings are based primarily on qualitative self-reported responses and thematic analysis, which may not fully capture the extent of students' systems-thinking capabilities or conceptual development. Finally, the study did not include a longitudinal assessment, making it difficult to determine whether the observed gains in systems-oriented reasoning persist over time or transfer to other engineering domains. Despite these limitations, the findings provide encouraging evidence that structured, framework-based interventions can support the development of broader, more integrated approaches to engineering problem-solving.

Future research could build upon these findings in several ways. The variation in response depth observed among students suggests that additional instructional scaffolding, such as structured response prompts, rubrics, or guided reflection activities, may further strengthen the development of systems-oriented reasoning. Future studies should also incorporate more formal quantitative measures of systems thinking, including rubric-based assessments or validated evaluation instruments, to complement qualitative analyses and strengthen the robustness of the findings. Expanding implementation across multiple courses, institutions, and student populations would improve external validity and enable comparisons across instructional contexts. Longitudinal research is also needed to examine whether gains in systems thinking are sustained over time and transferable to engineering problems beyond energy systems. Finally, integrating more explicit instruction in trade-off analysis, uncertainty, and quantitative decision-making may further enhance students' ability to navigate the complexities of real-world socio-technical challenges.

In summary, the findings suggest that integrating structured, interdisciplinary frameworks into engineering curricula can meaningfully enhance students’ reasoning regarding complex socio-technical systems. The observed shift from intuitive, moralized explanations to analytical, systems-oriented understanding represents a critical step toward preparing students for the multifaceted challenges of modern engineering practice.

6. Conclusion

This study demonstrated that a structured, framework-based approach can significantly enhance systems thinking among undergraduate engineering students. The framework provides an effective and practical tool for integrating management-oriented perspectives, technology, the environment, society, politics, and economics into traditional technical coursework. By embedding this framework in energy-focused case studies and complementing it with concepts such as CSR, ESG, and TBL, students developed a more comprehensive and structured understanding of complex socio-technical challenges.

Across multiple dimensions of analysis, problem definition, causal reasoning, and barrier identification, students exhibited a clear shift from simplistic, moralistic, and descriptive explanations toward more analytical, interconnected, and constraint-aware reasoning. Notably, students increasingly recognized the role of economic considerations, infrastructure limitations, regulatory environments, and environmental trade-offs, as well as the inherent difficulty of identifying a single or ideal solution. These findings suggest that the framework not only broadens the scope of student thinking but also supports deeper engagement with real-world complexity and implementation challenges.

Furthermore, the results indicate that integrating management frameworks into engineering education strengthens interdisciplinary competence and decision-making capabilities. Frameworks serve as an accessible bridge between engineering and management domains, enabling students to contextualize technical solutions within broader societal and institutional systems. This integration aligns with the evolving demands of modern engineering practices, in which professionals must navigate uncertainty, competing priorities, and multi-stakeholder environments.

Future research should extend this work with longitudinal studies to assess the persistence of systems-thinking gains over time and their transferability to domains beyond energy systems. Expanding implementation across multiple courses, disciplines, and institutions would provide greater insight into the approach's generalizability. Additionally, incorporating quantitative assessments and validated measurement tools would strengthen the empirical basis of evaluating learning outcomes. By continuing to refine and scale this framework-based approach, engineering education can better prepare students to address the complex, interdisciplinary challenges that define contemporary practice.

7. Disclosures

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INCREASING ETHICAL AWARENESS AMONG CIVIL ENGINEERING STUDENTS: A PILOT STUDY

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Abstract

Engineers must frequently make decisions during their careers without fully understanding all the consequences, which can lead to unintended or harmful outcomes. Therefore, engineers must consider the ethical dimensions of their decisions while working to satisfy their employer's interests, even if these decisions conflict with their organization's objectives or their own career aspirations. Engineers also have a responsibility to uphold ethical standards that build trust not only in themselves and their organization, but also in their profession. Students entering the workforce must uphold the same ethical standards expected of their profession. Therefore, it is crucial to educate students on the importance of ethics and its impact on their future careers. The current study examined the impact of an ethics module in an upper-level civil engineering course on students' ethical decision-making processes. The module consisted of a pre-survey administered at the start of the semester, a lecture on the principles of ethical decision-making and ethical considerations in the engineering workplace, and a post-lecture survey. In the surveys, students were presented with several scenarios that required them to make ethical judgments as engineers. Both surveys were designed to evaluate students' ethical behavior. The responses were analyzed using the Chi-square test of independence to determine whether ethics training had a significant impact on engineering students' ethical perspectives.

Keywords: *Ethics Training; Civil Engineering; Ethical Work Practices; Engineering Ethics*

1. Introduction

Civil engineering projects, especially large construction projects, often involve substantial capital

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and affect large groups of stakeholders. These factors leave the construction industry particularly vulnerable to unethical practices. For example, Agyekum et al. (2024) describe the construction process as fragmented, involving multiple groups from diverse professional fields and ethical backgrounds. As a result, the construction industry has been described as among the most corrupt (Tow & Loosemore, 2009; Transparency International, 2005). Bribery, bid rigging, tender manipulation, and conflicts of interest, among other violations of ethical duties and norms, are common (Adnan et al., 2012). These practices are unethical on their own terms and in terms of their harmful consequences, such as inefficient use of economic resources, lost opportunities for competitors and other businesses, and poor-quality completed projects (Rahman et al., 2007).

In general, engineers are known for their ability to design, test, and undertake projects of great value, but these projects often come at substantial cost; thus, they have considerable ethical responsibilities to clients, employers, and stakeholders. Beyond these responsibilities, engineers must frequently make decisions without fully understanding all possible consequences. The consequences of these decisions can be unintended or harmful. For example, in China, various structures, including bridges, a hotel, and a power plant platform, collapsed between 2006 and 2022, resulting in economic and human losses (Xu et al., 2024). Regarding unethical engineering and construction practices worldwide, Tow and Loosemore state, “the U.S. construction sector is no different” (p. 123, 2019) and cite examples from the United Kingdom, Australia, and Japan. Therefore, engineers must consider the ethical dimensions of their decision-making while working to satisfy their employer’s interests, even if these decisions conflict with their organization’s objectives or their own goals.

Engineers also have a responsibility to uphold ethical standards that build trust not only in their organization but also in their profession. Unethical behavior by engineers can erode public trust in engineers and their employers and reflect poorly on their respective professional fields. Students entering the workforce must also uphold the same ethical standards expected of their profession. Therefore, it is important to educate future generations of engineers about the importance of ethics and its impact on their intended careers, and to guide ethical decision-making. Such guidance and education should foster an understanding of ethical principles and equip individuals with the skills to make ethical decisions in a complex work environment, where such decisions can have devastating consequences.

This paper examines the impact of an ethics module in an upper-level civil engineering course (N = 317) on the students’ ethical decision-making processes. The module consisted of a pre-survey, a lecture on the principles of ethical decision-making and ethical considerations in the engineering workplace, and a post-lecture survey. The lecture introduced principles of engineering ethics, professional responsibility, licensure, and ethical decision-making, using scenario-based examples from engineering practice.

In the surveys, students were presented with several hypothetical ethical dilemmas from the construction industry that required them to make ethical judgments as engineers. Both surveys were designed to evaluate students’ ethical behavior. The pre-survey was distributed at the start of the semester. The same questionnaire was administered to students after attending the lecture on ethical decision-making and ethical considerations in the engineering workplace.

2. Literature Review

The need for ethical behavior in the construction industry is well established. Vee and Skitmore (2003) found that engineering and construction professionals frequently witness unethical conduct despite the presence of professional codes of ethics. Similarly, Tow and Loosemore (2009) identified the construction industry as particularly vulnerable to corruption and unethical business practices, including bribery and conflicts of interest. Research has also shown that unethical practices can negatively affect project quality, stakeholder trust, and organizational performance (Adnan et al., 2012; Rahman et al., 2007). These findings highlight the importance of preparing future engineers to recognize and respond appropriately to ethical dilemmas commonly encountered in professional practice.

The importance of ethics education in engineering curricula has also been widely discussed in the literature. Hess and Fore (2018) noted that engineering ethics interventions are often motivated by ABET accreditation requirements and industry expectations for ethical professionalism. Although some researchers have questioned the long-term effectiveness of ethics education (Davis, 2001; Abaté, 2011; Martin et al., 2024), many studies support the use of scenario-based ethics instruction to improve ethical awareness and recognition of ethical issues in professional practice (Zhu & Jesiek, 2017; Polmear et al., 2024). Chung and Alfred (2013) further reported that interactive ethics instruction can improve student learning outcomes compared to lecture-only approaches. Collectively, the literature suggests that ethics education can foster ethical awareness and professional responsibility among engineering students.

3. Research Methodology

The research methodology involved disseminating a pre-survey, delivering an ethics lecture, and then distributing a post-survey. The survey was designed to evaluate the degree of ethical behavior among students. The pre- and post-surveys were identical; students were presented with several hypothetical ethical dilemmas from the construction industry and asked to make ethical judgments as engineers. The lecture focused on ethical decision-making and workplace considerations.

To develop the surveys, a review of the relevant literature was conducted, and several common ethical issues were identified. These ethical issues were then adapted into 19 survey statements or scenarios. These statements or scenarios focus on regular work practices in the Civil Engineering field, including contracting, employer relations, client relations, and contractor relations. The statements and scenarios are provided in Table 1. Each statement or scenario used a five-point Likert scale (1=strongly disagree, 2=somewhat disagree, 3=neither agree nor disagree, 4=somewhat agree, 5=strongly agree).

Prior to distributing the survey, Institutional Review Board approval was obtained. The survey was then distributed to senior civil engineering students (N = 317) who were enrolled in a required senior seminar course. The survey was distributed via Qualtrics in the fall of year 1 (n = 164) and the fall of year 2 (n = 153). A total of 297 responded to the pre-survey (93.7% of those recruited) and 273 participated in the post-survey (86.1% of those recruited). All responses were anonymous.

The study used a within-subject pre- and post-survey design to evaluate the impact of an ethics lecture on the perspectives of a group of civil engineering students enrolled in a one-hour senior seminar course. The ethics lecture provided an overview of ethics, morality, engineering registration/licensure, the basic tenets of the engineering profession, and the code of ethics. Further, eight scenarios that engineers often face were discussed, along with the consequences of ethical violations. Table 2 summarizes the scenarios discussed in the ethics lecture for that course.

Table 1. Survey Questions and Scenarios

It is important to adhere to applicable laws and regulations even when unethical actions cannot be traced back to you.
Your obligation to your employer is secondary to your obligation to society.
During an open bid for a project, it is acceptable to work with other contractors to determine their bids.
It is acceptable to underbid on a contract and then add extras as you anticipate your subcontractors will do the same.
It is normal to show a subcontractor a rival's bid to obtain the best price for your firm.
As long as one's actions are not illegal, they are ethical.
Bad decisions made out of ignorance are just as unethical as those made out of greed.
Your peers influence the degree of your ethical behavior.
It is okay to share confidential information with one's partner if he/she does not work in the same industry.
It is more important to be ethical in public projects than in private projects, since you are spending tax dollars on the former.
One must place their client's interests above their employer's.
Slight misrepresentations of one's qualifications are acceptable if they can be easily acquired when needed.
It is sometimes acceptable to give small gifts to officials, as it is not equivalent to bribing, because you have no intention of swaying the official's decision on your project.
It is important to intervene when you see a colleague participating in unethical activities.
It is appropriate to accept small gifts from contractors who are bidding on your firm's projects.
Inappropriate behavior outside one's work environment reflects poorly on his/her employer.
It is acceptable to take travel funding from companies bidding for your firm's projects.
In a competitive bidding environment, it is acceptable to spread negative rumors about your rivals, as they are likely doing the same.
It is acceptable to take clients with you when moving from one firm to another.

A Chi-square test of independence was conducted to determine whether the ethics lecture resulted in a difference in the distribution of student responses between the pre- and post-surveys. The null hypothesis is that there was no difference in the response pattern between the pre- and post-surveys. In addition to statistical significance, Cramér's V was calculated as an effect size measure to assess the magnitude of differences between the pre- and post-survey response distributions.

Table 2. Eight Scenarios Discussed in the Ethics Lecture

As a professional engineer, you are in charge of the remediation of a site contaminated by a historical release. A nearby landowner approaches you to ask how the release and subsequent cleanup efforts will impact the health and well-being of his land. What are you permitted to disclose to the landowner at this time?
A recently finalized regulation impacts a design contract that you have already signed with a company that calls for the construction of a new copper smelter. To comply with the regulation, the project's cost would need to be increased. What are you ethically obligated to do?
A civil engineer with 10 years of experience reads a story in his local newspaper about the planned construction of a landfill in an area where he believes significant damage will be caused to a nearby wetland. What would be an acceptable course of action?
A design engineer at a German automobile manufacturing company discovers a minor flaw in an emissions test that may have led to his company's emissions being under-reported for many years. The engineer immediately informs his supervisor, who promises to address the issue. After two weeks, nothing has been done. What is the engineer ethically responsible for doing at this point?
An engineering professor with a professional engineering license and 20 years of experience in engineering education is asked to consult on a building design. Can the professor accept this request?
Complete the sentence: "State registration boards, boards of ethical review, oversight committees, and internal audit departments are used in industry and government because …"
Two engineers submitted sealed bids to a prospective client for a design project. The client told engineer "A" how much engineer "B" had bid and invited engineer "A" to beat that amount. Engineer "A" would like to perform the project and believes he is the best choice for the job. What should he do?
A local engineering professor serves as the technical advisor to the city council. A few weeks before the council is scheduled to award a large construction contract, the professor is approached by one of the competing companies and offered a consulting position. Under what circumstances would it be ethical to accept the job?

4. Results

The data were cleaned by excluding incomplete surveys and responses from participants who did not complete both the pre- and post-lecture surveys. A total of 297 complete surveys were available from the pre-survey, and 273 from the post-survey. The Chi-Square test does not require a paired comparison. Therefore, all pre- and post-survey data were used for the analysis. The number of responses to the questions in each category, and the Chi-Square test values are presented in Table 3.

Table 3. Chi-Square Test Results

	Questions	Strongly disagree		Somewhat disagree		Neither agree nor disagree		Somewhat agree		Strongly agree		Chi-Square Exact Significance	p-value	Cramer's V
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post			
1	It is important to adhere to applicable laws and regulations even when unethical actions cannot be traced back to you.	13	11	9	9	8	9	26	14	241	231	3.116	0.539	0.074
2	Your obligation to your employer is secondary to your obligation to society.	24	25	20	32	26	26	81	61	146	129	5.657	0.226	0.100
3	During an open bid for a project, it is acceptable to work with other contractors to determine their bids.	148	189	81	46	42	29	23	9	3	1	23.250	<0.001	0.202
4	It is acceptable to underbid on a contract and then add extras as you anticipate your subcontractors will do the same.	173	197	85	61	23	11	12	3	4	1	15.955	0.003	0.167
5	It is normal to show a subcontractor a rival's bid to obtain the best price for your firm.	202	220	57	34	27	14	11	4	0	1	13.984	0.007	0.157
6	As long as one's actions are not illegal, they are ethical.	184	192	93	64	14	14	5	4	1	0	5.721	0.221	0.100
7	Bad decisions	16	15	64	53	44	28	97	87	76	90	5.345	0.254	0.097

	made out of ignorance are just as unethical as those made out of greed.													
8	The degree of your ethical behavior is influenced by your peers'.	62	58	39	39	38	28	127	116	30	32	1.283	0.864	0.047
9	It is okay to share confidential information with one's partner if he/she does not work in the same industry.	156	166	92	75	26	20	19	11	4	1	5.065	0.281	0.094
10	It is more important to be ethical in public projects than in private projects, as you are spending tax dollars on the former.	157	151	64	47	35	34	32	29	9	12	2.305	0.680	0.064
11	One must place their client's interests before their employer's.	11	23	68	75	107	80	81	63	30	32	9.798	0.044	0.131
12	Slight misrepresentations of one's qualifications are acceptable if they can be easily acquired when needed.	156	170	83	72	34	17	23	12	1	1	9.426	0.051	0.129
13	It is sometimes acceptable to give small gifts to officials, as it is not equivalent to bribing, because you have no	132	160	84	56	36	34	39	19	4	3	14.472	0.006	0.159

	intention of swaying the official's decision on your project.													
14	It is important to intervene when you see a colleague participating in unethical activities.	2	1	3	2	11	10	93	62	188	196	5.770	0.217	0.101
15	It is appropriate to accept small gifts from contractors who are bidding on your firm's projects.	165	171	73	58	34	25	22	13	3	4	4.474	0.346	0.089
16	Inappropriate behavior outside one's work environment reflects poorly on his/her employer.	1	4	14	7	18	13	120	90	144	157	8.615	0.071	0.123
17	It is acceptable to take travel funding from companies bidding for your firm's projects.	140	158	79	62	55	37	21	10	1	3	10.389	0.034	0.135
18	In a competitive bidding environment, it is acceptable to spread negative rumors about your firm's rivals, since they are likely doing the same.	261	235	24	19	8	13	2	1	1	3	3.372	0.498	0.077
19	It is acceptable to take clients with you when moving from one firm to another.	72	84	61	78	102	68	53	34	8	7	12.941	0.012	0.151

Of the 19 statements or scenarios, responses differed significantly for seven. Student responses were significantly different when students were asked whether it is acceptable to work with other contractors to determine their bids (Question 3, p-value < 0.001). There was a significant change in the response pattern in the acceptability of underbidding on a contract and then adding extras (Question 4, p-value < 0.003). In addition, the response patterns differed, with a subcontractor showing a rival's bid to obtain the best price (Question 5, p-value < 0.007). Students also responded differently about giving small gifts to officials (Question 13, p-value < 0.006), with more ethical choices in the post-survey. There was also a significant difference in student responses regarding the acceptability of accepting travel funding from companies bidding for their firm's projects (Question 17, p-value < 0.034) between the pre- and post-surveys; a greater number of students leaned towards making ethical choices after attending the ethics lecture. After the ethics lecture, more students indicated that taking clients with them to a new firm was not acceptable (Question 19, p-value < 0.012). While there was a significant difference in student response patterns regarding placing client interests before employer interests (Question 11, p-value < 0.044), the responses remained neutral and did not move towards strongly disagree or strongly agree.

Although only seven of the nineteen scenarios demonstrated statistically significant changes, these scenarios represent several of the most consequential ethical issues encountered by practicing civil engineers, including competitive bidding practices, conflicts of interest, acceptance of gifts, and professional relationships with clients. Improvements in students' recognition of these issues may contribute to stronger professional judgment and better prepare students to recognize and respond appropriately to ethical dilemmas encountered in professional practice. While the statistical differences were observed following a relatively brief educational intervention, the practical significance lies in reinforcing ethical decision-making for situations that engineers are likely to encounter throughout their careers. Cramér's V was calculated for all survey items to assess the magnitude of the observed differences between the pre- and post-survey response distributions (Table 3). Cramer's V values ranged from 0.047 to 0.202, with the seven statistically significant items ranging from 0.131 to 0.202. Although these represent small effect sizes, they are educationally meaningful given that the intervention consisted of a single ethics lecture.

An interesting finding is that significant improvements occurred primarily for scenarios involving industry-specific ethical practices, including bid rigging, contractor relationships, conflicts of interest, gifts from vendors, and client solicitation. These situations represent nuanced professional dilemmas that students may have had limited exposure to prior to the ethics lecture. In contrast, broader ethical principles such as obeying laws, protecting confidential information, and intervening when unethical behavior is observed have already received highly ethical responses in the pre-survey. This pattern suggests a ceiling effect, in which students entered the course with strong general ethical awareness but benefited most from instruction that addressed complex workplace situations unique to engineering practice.

5. Conclusions And Limitations

This study evaluated the impact of an ethics instruction module on students' awareness and perspectives towards ethical work practices in the engineering field. A Chi-Square test was used to analyze differences in responses to various ethical scenarios and in practice, pre- and post-ethics training. The study results suggest that most students were able to make appropriate ethical choices across most scenarios before taking the ethics training module. However, they still improved their awareness and integrity regarding potential corruption or unethical business practices in the construction industry.

From an educational perspective, these findings suggest that a single ethics intervention can strengthen students' understanding of complex professional situations even when general ethical awareness is already well developed. Engineering programs should consider incorporating multiple scenario-based ethics modules throughout the curriculum rather than relying on a single ethics lecture. Integrating authentic industry cases into technical courses may further improve students' ability to recognize conflicts of interest, procurement ethics, professional responsibility, and ethical decision-making in practice. Such approaches also support ABET outcomes related to ethical and professional responsibility.

However, this study has several limitations that warrant consideration and attention in future work in this area. First, the study only included senior engineering students from the civil engineering department. Students in other engineering disciplines should also be assessed for their understanding and awareness of workplace ethics. Next, the evaluation period was limited to two semesters. Consequently, the authors intend to continue this line of research by collecting additional data and refining the surveys and scenarios developed for this intervention. Third, the surveys were anonymous; therefore, paired tests could not be conducted. It would be interesting to compare responses by individual and by demographic characteristics, such as work experience and GPA. Further, the pre-survey was conducted one to two weeks prior to the ethics lecture, and the post-survey was conducted one to two weeks after the ethics lecture. The short time frame may have resulted in fewer pre-post differences. There is also a potential limitation of primacy and recency effects upon memory and recall. Distributing the surveys farther from the ethics lecture may lead to greater differences in responses. Therefore, conducting the study over additional semesters and including students from different engineering departments may provide more information about the ethics lecture's impact. Moreover, given the results from Anonymous (2016) on academic dishonesty, it would also be of interest to conduct a similar evaluation of students in lower-level courses to determine whether professional ethical awareness changes as students' progress through their engineering program of studies. Evaluation of different instructional modes and the development of interactive case study approaches will be considered in future work.

Overall, the findings demonstrate that even a relatively brief ethics intervention can improve students' recognition of several complex ethical issues commonly encountered in civil engineering practice. While students entered the course with strong general ethical awareness, targeted instruction was particularly effective in strengthening their understanding of industry-specific ethical dilemmas involving bidding practices, conflicts of interest, and professional responsibility. These findings support continued integration of scenario-based ethics instruction throughout engineering curricula and provide evidence that ethics education can reinforce ethical decision-making skills needed for professional practice.

6. Disclaimer Statements

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MULTI-DIMENSIONAL FRAMEWORK FOR INDUSTRY 5.0: INTEGRATING HUMAN-CENTRIC, SUSTAINABILITY, AND OPERATIONAL RESILIENCE

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Abstract

Industry 5.0 reframes digital transformation as a socio-technical endeavor in which automation serves human capabilities, environmental limits, and operational continuity. Yet, much of the current discourse remains either conceptual—lacking implementable metrics—or technology-centric—treating humans and sustainability as constraints instead of design objectives. This paper develops a multi-dimensional implementation framework that operationalizes the three pillars of Industry 5.0: human-centricity, sustainability, and operational resilience. We synthesize recent advances in collaborative robotics and safety-aware human–robot collaboration, digital twins (including human and supply-chain twins), and AI-driven decision support—augmented by emerging 6G ultra-reliable low-latency networking capabilities such as reconfigurable intelligent surfaces, terahertz communications, multi-access edge computing, and semantic communication. The proposed framework introduces a closed-loop "sense–simulate–decide–act–learn" operating logic that links real-time shop-floor data, what-if simulation, and multi-objective optimization across the three pillars. Beyond architecture, the paper contributes an evaluation protocol and a roadmap that translate high-level principles into measurable indicators suitable for managerial governance and engineering deployment. The study concludes with adoption barriers and research directions focused on trustworthy AI, human digital twins, and sustainable edge intelligence for the next generation factory.

Keywords: *Industry 5.0; Human–Robot Collaboration; Collaborative Robotics; Digital Twins; Human Digital Twin; Sustainable Manufacturing; Operational Resilience; 6G URLLC; Edge Computing; Semantic Communication; Reconfigurable Intelligent Surfaces; Artificial Intelligence*

1. Introduction

Industrial revolutions can be read as successive reorganizations of the relationship between people, energy, and information. Industry 1.0 mechanized manual labor; Industry 2.0 electrified and scaled it through mass production; Industry 3.0 embedded computation and automation; and Industry 4.0 connected cyber–physical production systems (CPPS) through ubiquitous sensing, industrial internet platforms, and data-driven optimization. Industry 5.0 is not merely the next

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technology stack in this sequence, but a shift in design intent: digital systems are evaluated by how well they augment human creativity and well-being, reduce ecological burdens, and maintain continuity under disruption rather than only by throughput or cost efficiency. Early articulations of Industry 5.0 emphasized "human-centricity" as the corrective to automation-driven displacement, while more recent work argues that resilience and sustainability must be co-equal pillars because factories now operate under simultaneous climate, geopolitical, cyber, and pandemic-era shocks.

A central limitation of many Industry 4.0 deployments is that they optimize for efficiency under stable assumptions. Highly automated and tightly coupled systems can become brittle when demand volatility, supplier failures, energy constraints, or cyber incidents invalidate those assumptions. At the same time, purely technology-centric roadmaps often treat humans as "operators of last resort" rather than as dynamic agents whose tacit knowledge, trust, and situational awareness are indispensable for safe and adaptive production. This mismatch became visible in post-COVID recovery efforts, where manufacturers sought not only to digitize but to build flexible capacity, reduce dependency risk, and reconfigure operations while meeting stricter sustainability expectations.

The research gap addressed in this paper is the absence of an integrated, implementable framework that simultaneously operationalizes human-centricity, sustainability, and resilience. Existing contributions often focus on one pillar—e.g., human–robot collaboration (HRC) or green manufacturing—without specifying the governance mechanisms that reconcile trade-offs among pillars, or the digital infrastructure required to measure and optimize them together. Recent surveys on Industry 5.0 and its enabling technologies highlight this fragmentation and call for frameworks that translate principles into deployable system architectures, metrics, and adoption pathways.

Accordingly, the paper contributes (i) a multi-dimensional Industry 5.0 implementation framework that couples the three pillars through a closed-loop operating logic, (ii) a 6G-driven reference architecture for ultra-reliable low-latency human-centric collaboration and digital-twin synchronization, (iii) an evaluation protocol that links each pillar to measurable indicators, and (iv) a phased implementation roadmap intended to support managerial planning and engineering execution. The framework is proposed as an original synthesis that extends prior single-pillar roadmaps by making the coupling mechanisms explicit and by emphasizing governance and measurement as first-class design elements.

2. Literature Review: From Industry 4.0 to Industry 5.0

2.1 Defining Industry 5.0 and Its Three Pillars

Industry 5.0 is frequently introduced as "beyond Industry 4.0", yet the distinction is not primarily technological. Industry 4.0 tends to interpret connectivity, automation, and analytics as pathways to efficiency and productivity, whereas Industry 5.0 treats these capabilities as means to human welfare, ecological integrity, and continuity of value creation under disruption. The human-centric component emphasizes that industrial systems should be designed around human needs, capabilities, and limitations—physically (safety and ergonomics), cognitively (workload and attention), and socially (trust, autonomy, and meaningful work). Sustainability extends environmental metrics beyond compliance, embedding energy, carbon, and circularity considerations directly into production planning and product design decisions rather than treating them as downstream reporting activities. Resilience, in turn, reframes operational excellence as the ability to absorb shocks, recover rapidly, and adapt structures when operating conditions permanently change; this dimension has been formalized as a "viability-based" integration of resilience, sustainability, and human-centricity.

A critical observation in the recent literature is that these three pillars cannot be pursued independently because they interact through shared resources and constraints. For example, aggressive automation can reduce short-term cost but may degrade resilience if the system becomes dependent on narrow suppliers of proprietary components and may degrade human centricity if it increases monitoring burden or deskills operators. Conversely, a sustainability intervention such as local sourcing may improve carbon performance while increasing resilience (shorter supply chains) or decreasing it (smaller supplier base) depending on network design. This coupling motivates frameworks that treat Industry 5.0 as a multi-objective design problem rather than a checklist of technologies.

2.2 Human–Machine Collaboration and the Cobot Revolution

Human–robot collaboration is often presented as the emblematic technology of Industry 5.0 because it operationalizes augmentation: robots provide strength, precision, and repeatability, while humans provide context, dexterity, and judgment. Collaborative robots (cobots) differ from traditional industrial robots not only by safety features but by their participation in shared workspaces and their requirement to negotiate task allocation in real time. Recent HRC research has moved beyond classical "physical separation" to dynamic safety assurance, where perception and control continuously enforce safe separation, safe speed, or power/force limiting. Systematic reviews emphasize that effective HRC requires both technical safety measures and organizational processes including risk assessment, operator training, and human factors engineering.

A major 2024–2025 trend is the convergence of cobots with language and vision–language models, which act as cognitive interfaces for natural interaction. Surveys in intelligent manufacturing argue that large language models (LLMs) reduce the expertise barrier by enabling instruction, troubleshooting, and documentation through conversational interaction, aligning with the human-centric ethos of Industry 5.0. In robotics, natural language models and embodied AI approaches are being explored to translate high-level human intent into sequences of robot actions, while incorporating perception feedback to handle uncertainty. This transition can be interpreted as a shift from "programming" robots to "negotiating" with them: the user expresses goals and constraints, the system proposes plans, and humans validate or override decisions. However, the same literature warns that LLM-driven autonomy introduces new risks—hallucinated actions, brittle grounding, and opaque failure modes—making guardrails and verification essential for safety-critical industrial use.

A second trend concerns wearable-assisted collaboration and human digital twins (HDTs), where sensing of posture, fatigue proxies, and task context supports ergonomic adaptation and safety monitoring. HDTs provide a computational representation of human state and constraints that can be used to optimize task allocation and to evaluate interventions in simulation before deployment. Recent surveys on human digital twins highlight their role in Industry 5.0 for worker-centric optimization—e.g., balancing productivity with musculoskeletal risk—while also noting privacy and governance challenges when human data becomes a production input.

2.3 Sustainability Integration: From Green Manufacturing to Carbon-Aware Operations

Industry 5.0 sustainability differs from conventional "green manufacturing" in that it requires sustainability objectives to be co-optimized with productivity and service levels in real time. The enabling mechanism is data: energy meters, machine states, process parameters, and product genealogy data are fused to estimate energy and carbon intensity at a granularity usable by planning and control algorithms. In this setting, digital twins are not only used for throughput optimization but for carbon-aware what-if analysis, such as evaluating alternative process plans, scheduling policies, and maintenance decisions that influence scrap rates and energy peaks. Recent Industry 5.0 roadmaps emphasize that sustainability targets must be encoded as operational constraints (e.g., carbon budgets per batch, renewable-energy availability windows) and as incentives (e.g., carbon cost in objective functions) rather than as end-of-year reporting metrics.

The interaction between sustainability and human-centricity is also increasingly foregrounded. For instance, ergonomic improvements that reduce fatigue may reduce error and rework, indirectly lowering material and energy waste. Conversely, sustainability interventions that increase manual handling—such as adding reverse logistics or remanufacturing steps—can increase ergonomic risk if not paired with assistive robotics or redesigned workstations. This motivates "human-and-planet co-design", where lifecycle and ergonomics analyses are coupled early in the system engineering process. Such coupling becomes feasible when digital twin platforms incorporate both environmental models and human capability models, enabling joint optimization rather than siloed improvements.

2.4 Resilience in Supply Chain 5.0: From Efficiency to Viability

Operational resilience in the Industry 5.0 context extends beyond supply chain risk mitigation to include cyber resilience, energy resilience, and the capacity to reconfigure production under constraint. The viability perspective is particularly relevant: rather than optimizing a single performance metric, the system seeks to maintain acceptable performance levels across multiple dimensions during and after disruption, possibly by changing structure (e.g., switching suppliers, routing production to alternative sites, or changing product mix). This lens complements sustainability, because disruptions increasingly include climate-driven events that directly affect energy supply and logistics. Digital twins of supply networks are often proposed as the computational core for resilience because they enable scenario generation, stress testing, and evaluation of response policies under uncertainty.

A distinguishing feature of Industry 5.0 supply networks is the demand for mass personalization alongside resilience. Personalized products reduce economies of scale and increase variant complexity, making planning under disruption more challenging. Human–machine collaboration offers a pathway to manage this complexity by combining human judgment in exception handling with AI-driven analytics for detection and prediction. The practical implication is that resilience cannot be "bolted on" via buffers alone; instead, it must be embedded into sensing, decision rights, and the digital infrastructure that supports rapid coordination across organizational boundaries.

2.5 Technology Enablers: Digital Twins, 6G, Blockchain, Big Data, and IoRT

The enablers most consistently associated with Industry 5.0 include (i) digital twins spanning assets, processes, humans, and supply chains; (ii) AI for perception, planning, and decision support; (iii) cloud–edge computing to meet latency and privacy constraints; (iv) secure data sharing mechanisms such as blockchain and data spaces; and (v) next-generation connectivity to synchronize cyber–physical operations in real time. Digital twins are central because they provide the "safe sandbox" for evaluating trade-offs across the three pillars: production alternatives can be simulated without exposing workers or assets to risk, and sustainability/resilience effects can be assessed before real-world rollout. Industry 5.0-focused surveys highlight that the next step is not more data, but trustworthy integration: model governance, uncertainty quantification, and feedback loops that prevent drift when operating conditions change.

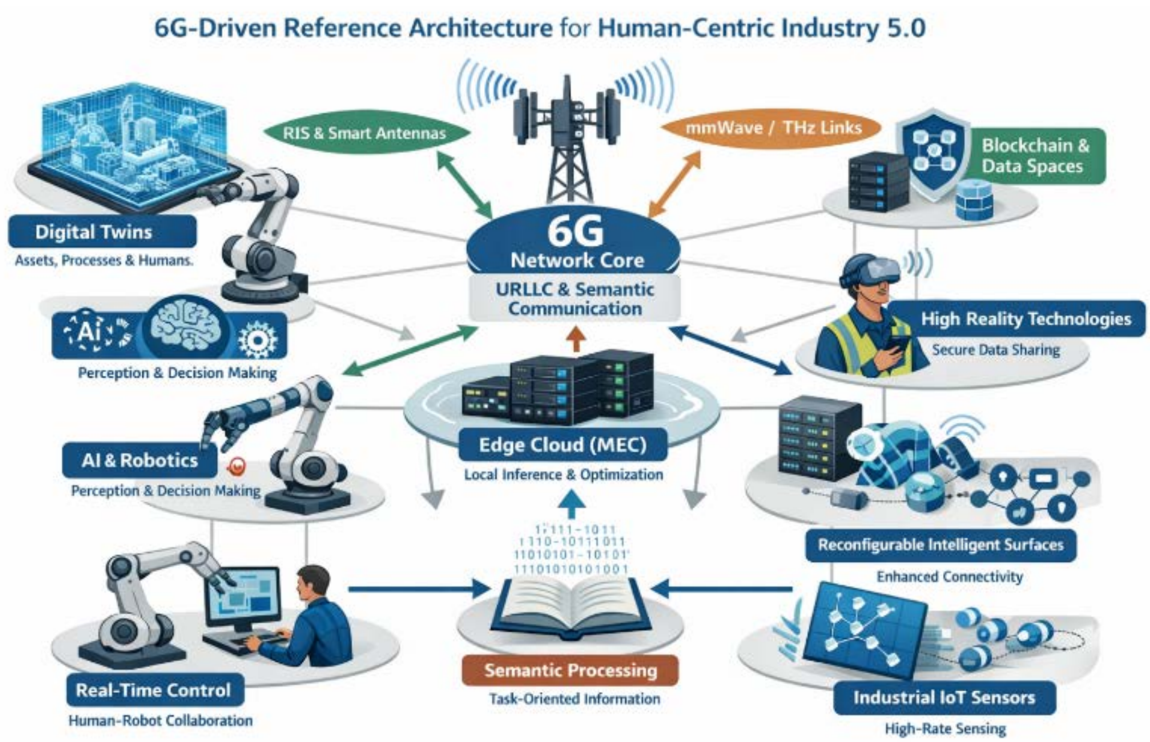

Fig. 1. 6G-Driven Reference Architecture for Human-Centric Industry 5.0

Connectivity is increasingly recognized as a limiting factor for human-centric collaboration because safety and responsiveness require deterministic communication and tight closed-loop control. Fig. 1 summarizes a 6G-driven reference architecture in which ultra-reliable low-latency communication (URLLC) and deterministic scheduling support real-time HRC, extended reality training, and remote assistance, while multi-access edge computing (MEC) hosts time-critical inference and optimization near the shop floor. Reconfigurable intelligent surfaces (RIS) and smart radio environments are proposed to improve coverage and reliability in cluttered industrial spaces, complementing mmWave and terahertz (THz) links for high-rate sensing and digital twin synchronization. Recent surveys emphasize that semantic communication—the transmission of meaning rather than raw bits—can reduce latency and improve efficiency by prioritizing task-relevant information, which is attractive for industrial systems where redundant sensor data can saturate networks. On the computing side, resource allocation surveys show how MEC can be formulated to support URLLC guarantees, including task offloading and contention management mechanisms, and report open challenges for 5G/6G industrial deployment.

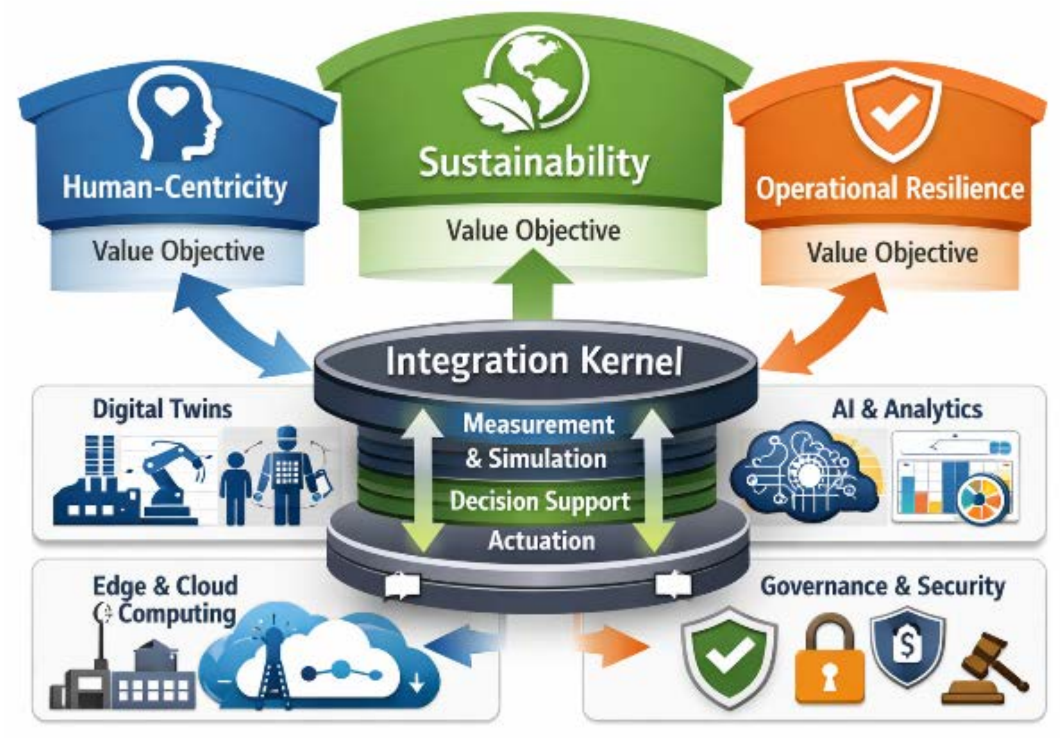

Fig. 2. Proposed Multi-Dimensional Industry 5.0 Implementation Framework

3. Conceptual Framework for Industry 5.0 Implementation

3.1 Three-Pillar Architecture and the Integration Kernel

Building on the three-pillar consensus, we propose an implementation view that separates "what Industry 5.0 aims to achieve" (the pillars) from "how it is executed" (the integration kernel). As illustrated in Fig. 2, the pillars—human-centricity, sustainability, and operational resilience—define the value objectives, while the integration kernel provides the socio-technical infrastructure that links measurement, simulation, decision support, and actuation. The kernel contains four tightly coupled subsystems: (i) multi-scope digital twins (asset/process/human/supply chain), (ii) AI/analytics for perception and decision support, (iii) edge–cloud orchestration and next-generation networking for real-time synchronization, and (iv) governance mechanisms spanning safety assurance, cybersecurity, privacy, and ethics. This separation is important because it clarifies that a factory can adopt advanced technologies (e.g., a digital twin) without becoming "Industry 5.0" unless those technologies are explicitly optimized against the three pillars and governed accordingly.

The integration kernel is designed to support trade-off-aware optimization. In practice, each decision point in a production system—task assignment in an HRC cell, lot sizing, maintenance scheduling, supplier selection—can be represented as a multi-objective optimization problem. Let "H" denote a human-centric cost (e.g., ergonomic risk, cognitive load proxy), "S" a sustainability cost (e.g., energy or carbon intensity), and "R" a resilience benefit (e.g., time-to-recover reduction or viability margin). The industry 5.0 decision problem is then to select actions that minimize {H, S, economic cost} and maximize {R, quality}, subject to safety constraints and operational deadlines. The practical novelty is not the existence of multi-objective optimization, but the insistence that H and S are first-class terms, not constraints or externalities. Fig. 2

therefore embeds the kernel at the center of the three pillars to emphasize that the coupling occurs through shared data models and shared control policies.

3.2 Operationalization Mechanisms: Closed-Loop Learning and Pillar Coupling

Figure 2 also proposes a closed-loop operating logic—sense, simulate (twin), decide, act, and audit/learn—that is intended to make Industry 5.0 deployable. The "sense" step integrates heterogeneous data sources: machine telemetry, energy meters, quality measurements, environmental sensors, and human-centric data such as workstation observations or wearable signals when ethically and legally permissible. The "simulate" step uses digital twins to evaluate alternative actions and to estimate their impacts not only on throughput but on ergonomic exposure, carbon intensity, and disruption response. The "decide" step executes multi-objective optimization or policy selection, potentially including human-in-the-loop decision rights for safety-critical or ethically sensitive choices. The "act" step enacts changes through automation controllers, cobots, scheduling systems, and supply chain coordination mechanisms. Finally, the "audit/learn" step continuously validates model accuracy, detects drift, and refines policies; this is essential because Industry 5.0 targets are sensitive to contextual changes such as workforce composition, energy mix, and supplier reliability.

To operationalize coupling, we propose an evaluation protocol that associates each pillar with a compact indicator set and then enforces explicit reconciliation at decision points. Human-centric indicators should include safety (incident/near-miss rates), ergonomics (risk indices derived from posture and load), competence development (training coverage and skill progression), and trust/acceptance (validated survey instruments and observed override rates). Sustainability indicators should include energy intensity, carbon intensity, material yield, and circularity proxies (reuse/remanufacture rates). Resilience indicators should include time-to-detect, time-to-respond, time-to-recover, and a viability margin reflecting the ability to maintain acceptable service levels under scenario stress tests. The key methodological step is to require that digital twins compute these indicators for each alternative action, turning value principles into computable objectives. This protocol is particularly powerful in HRC contexts because task allocation changes simultaneously affect ergonomics (H), energy and scrap (S), and response capacity (R).

Finally, the framework introduces a governance layer as a coupling mechanism rather than an afterthought. Trustworthy Industry 5.0 systems require that safety cases, cybersecurity controls, privacy-preserving data processing, and explainability requirements are embedded into architecture and procurement. For example, if LLM-based interfaces are used to support operators, they should be deployed with domain constraints, retrieval from verified sources, and logging that supports post-incident auditing; similarly, human digital twin implementations require data minimization and consent-aware processing to prevent the worker from becoming a surveilled object. In this sense, governance is the "fourth dimension" that determines whether the three pillars can be achieved sustainably over time.

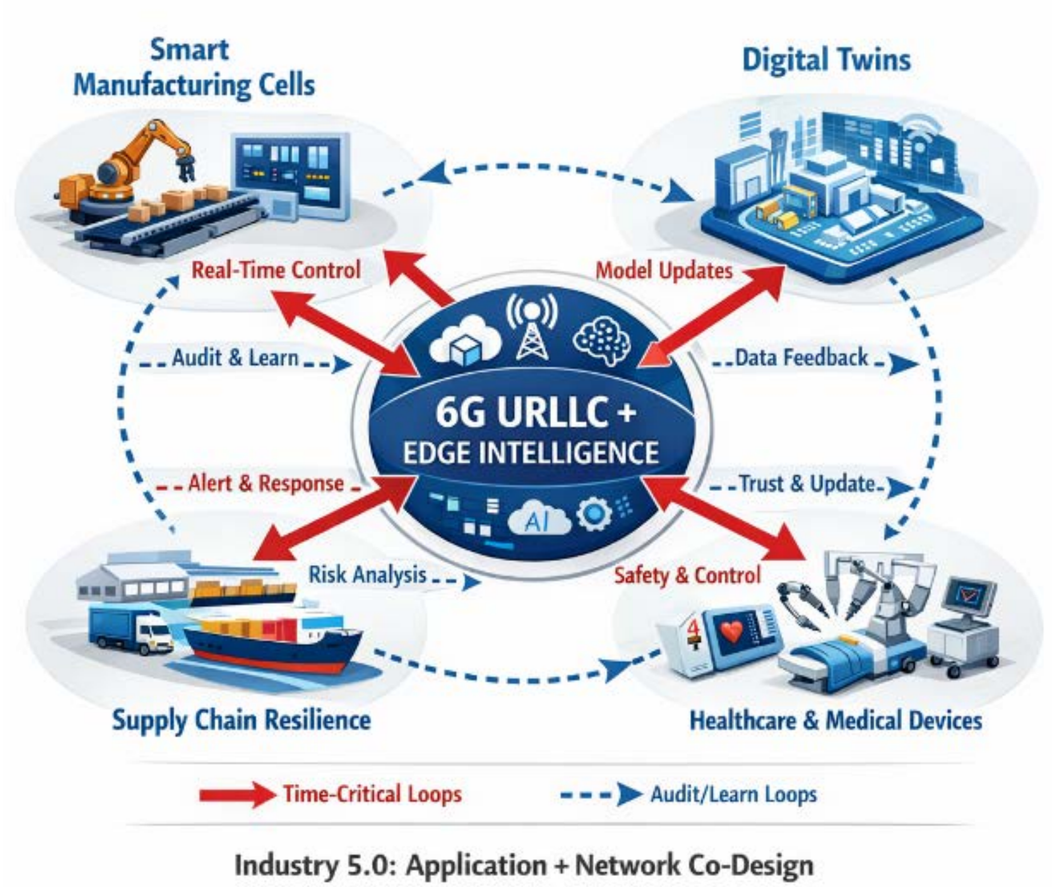

Fig.3. Evidence-linked application map for Industry 5.0 URLLC

4. Key Applications and Case Evidence

Industry 5.0 is often presented as a shift from technology-driven automation to human-centric, sustainable, and resilient industrial systems. In URLLC-enabled factories, this shift becomes visible in how evidence is generated, transported, and acted upon: safety events, quality signals, and trust-relevant provenance must be processed with predictable latency, while longer-horizon learning updates models and governance rules. The following sub-sections summarize four application areas with the clearest case evidence and a common dependence on 6G URLLC and edge intelligence.

Fig. 3 summarizes this relationship by positioning (i) smart manufacturing cells, (ii) digital twins, (iii) supply-chain resilience, and (iv) healthcare/medical-device contexts around a shared 6G URLLC + edge intelligence core. The solid arrows capture time-critical loops that must preserve bounded tail latency and ultra-high availability (e.g., emergency stops, quality gating, secure event alerts), whereas the dashed arrows represent the slower audit/learn loop that updates task allocations, twin parameters, and trust rules based on observed near-misses and drift. This visualization clarifies why 'application' and 'network' cannot be separated in Industry 5.0: each domain's value depends on which evidence is processed locally at the edge, which evidence is compressed or abstracted before leaving the site, and how these choices are reflected in a verifiable safety and sustainability case.

4.1 Human-Robot Work Cells

The most mature application domain for Industry 5.0 is the transformation of discrete manufacturing cells into human-centric work-cells where cobots and people share tasks rather than simply substituting labor. Many organizations start with pilot deployments in low-risk, well-bounded activities (e.g., pick-and-place, screwdriving, machine tending) because hazards are easier to assess and the performance envelope is repeatable. Moving toward Industry 5.0 maturity requires collaborative task sharing: robots take repetitive, high-force, or high-precision subtasks, while operators retain perception-intensive decisions, dexterous manipulation, and exception handling. Recent HRC surveys indicate that sustained performance depends on explicit task-allocation logic, on-line perception (e.g., depth sensing), and control policies such as speed-and-separation monitoring, supported by standardized risk assessment and safety validation procedures.

A concrete mechanism for human-centric improvement is to integrate ergonomics assessment into the same planning and control loop. Human digital twins and wearable sensing can estimate posture-related risk and fatigue proxies, enabling scheduling systems to alternate tasks, adjust pace, or trigger assistive interventions. The contribution of Industry 5.0 is that such ergonomics signals become optimization inputs rather than after-the-fact compliance reports. However, surveys on human digital twins emphasize that the limiting factor is not sensor availability but the reliability and governance of human models: ergonomic indices must be validated for the intended population, and privacy-preserving processing should be designed such that only necessary aggregates are used for operational decisions.

4.2 Digital Twins for Quality, Maintenance, and Energy-Aware Control

Digital twins have been widely adopted under Industry 4.0 for predictive maintenance and process optimization, yet Industry 5.0 extends their purpose by adding human-centric and sustainability objectives. In practice, this means that the same twin used to predict a machine fault is also used to estimate the quality and energy implications of alternative maintenance actions (e.g., running to failure versus early maintenance), and to simulate the downstream workload impacts on human operators during maintenance windows. Recent surveys on LLMs in intelligent manufacturing suggest a complementary role: LLMs can act as a knowledge interface that retrieves maintenance procedures, generates contextual checklists, and supports human diagnosis, particularly when integrated with verified documentation and digital-twin state.

Energy-aware control becomes more feasible when digital-twin models are coupled with edge intelligence. Hosting key elements of twin-state estimation and inference at the MEC layer supports tighter synchronization and faster adaptation of set-points (e.g., avoiding energy peaks or aligning energy-intensive operations with renewable availability windows). This architecture also strengthens sustainability-quality coupling: early detection of quality deviations reduces scrap and the embodied carbon of wasted material. Importantly, the literature cautions that these benefits require calibrated models and continuous validation; otherwise, optimization can chase spurious correlations and undermine operator trust.

4.3 Supply Chain 5.0: Resilience Analytics, Viability, and Secure Data Sharing

In supply networks, Industry 5.0 applications prioritize disruption detection, scenario planning, and rapid reconfiguration while maintaining sustainability targets. The viability-based view argues that supply chains should be stress-tested against multi-hazard scenarios, and that structural adaptation is often required to maintain acceptable service levels. Digital twins of supply chains enable such stress testing by simulating lead times, capacity constraints, and alternative sourcing strategies. When integrated with shop-floor twins, they support end-to-end 'what-if' evaluation-for example, whether switching a supplier increases embodied carbon, changes quality variability, or alters human workload due to different handling requirements.

Secure and trusted data sharing is a prerequisite because resilience analytics often require cross-organizational visibility. Academic work points to blockchain and industrial data spaces as potential mechanisms for provenance and access control, especially when combined with privacy-preserving analytics. Industry 5.0 governance, however, requires a pragmatic stance: the value of security sharing must be balanced against integration cost and latency, so hybrid designs are common in which edge platforms host local inference while only aggregated or verified events are shared with partners.

4.4 Healthcare and Medical Devices: Personalization Under Safety Constraints

Although this paper focuses on manufacturing, Industry 5.0 principles are increasingly applied in healthcare and medical-device contexts, where personalization is valuable, but safety is non-negotiable. Human-centricity extends to patient-centric design and clinician-friendly interfaces, while resilience concerns include supply continuity for critical devices and the ability to ramp production during emergencies. The relevance to the manufacturing sector is methodological: healthcare highlights the importance of safety cases, traceability, and explainability for AI-assisted decisions-requirements that are increasingly mirrored in regulated industrial environments. Cross-domain learning can therefore accelerate the development of trustworthy Industry 5.0 practices.

From an evidence-processing perspective, healthcare provides an extreme test case for combining personalization with strong constraints on latency, integrity, and auditability. Networked medical devices and connected-care workflows require time-critical alarms, quality gating, and (in some applications) teleoperation-like feedback loops, while sensitive data must remain protected. Here, URLLC-grade connectivity and edge intelligence are enabling rather than optional: edge-hosted inference can keep patient data local, provide clinician-facing explanations at the point of care, and generate high-integrity audit trails. Crucially, model updates and personalization policies must be managed as controlled changes: drift monitoring, versioning, and end-to-end traceability (data-model-action) become part of the safety case. This pattern translates directly to industrial deployments where AI begins to affect safety-relevant control and sustainability reporting.

5. Challenges and Barriers to Adoption

5.1 Technological Challenges: Interoperability, Latency, and Cybersecurity

A recurring technical barrier is interoperability between legacy equipment and modern digital platforms. Many factories still operate with heterogeneous PLCs, proprietary fieldbuses, and fragmented data models, making it difficult to build coherent digital twins or to deploy AI models that require consistent semantics. This challenge is compounded by the requirement of low latency and high reliability for safe collaboration: if perception or control signals are delayed, a cobot cell must fall back to conservative safety modes, reducing productivity and increasing operator frustration. The 6G-driven architecture in Fig. 1 illustrates why connectivity and edge computing are not optional add-ons but core enablers; URLLC and deterministic scheduling aim to provide predictable timing for closed-loop human–robot systems, while MEC hosts time-critical inference near the point of action.

Cybersecurity and data privacy constitute an additional technological barrier because Industry 5.0 expands the attack surface. Human-centric systems often integrate wearables, AR devices, and human digital twins, which introduce sensitive personal data into operational workflows. Meanwhile, resilience analytics and supply chain twins require data sharing across organizational boundaries. The literature emphasizes that security must be “by design” and “by default,” including segmentation, authentication, secure update mechanisms, and continuous monitoring. Importantly, security is also a human factors issue: confusing interfaces or opaque AI recommendations can lead to unsafe workarounds.

5.2 Human and Organizational Challenges: Skills, Trust, and Change Management

Industry 5.0 adoption is often constrained by workforce readiness. Cobots and digital twins change job content: operators may spend less time on manual handling and more time on supervision, exception handling, and interaction with AI systems. Without systematic upskilling and participatory design, this transition can be experienced as loss of control or deskilling, reducing acceptance and undermining safety. Surveys on human digital twins and LLM-based manufacturing assistance highlight the need for transparent decision support, clear responsibility allocation, and training that focuses on human–AI teaming rather than tool usage alone.

Trust is a particularly fragile resource in HRC systems. If operators perceive cobots as unpredictable, they will increase separation, reduce collaboration, and may bypass intended workflows—counteracting productivity and human-centric goals. Conversely, over-trust in AI recommendations can lead to complacency if systems fail silently. Systematic reviews of HRC safety stress that effective collaboration requires not only technical safety measures but also organizational processes such as iterative risk assessment, incident learning, and clear escalation paths. Industry 5.0 therefore demands change management that treats technology deployment as a socio-technical redesign rather than as a procurement project.

5.3 Economic Challenges: Investment, ROI Uncertainty, and SME Constraints

The economic barrier is not simply the cost of technology but the uncertainty of return on investment when benefits are multi-dimensional and long-term. Human-centric benefits such as reduced fatigue or higher job satisfaction are real but harder to monetize than throughput gains; sustainability benefits may depend on carbon pricing or customer willingness to pay; resilience benefits appear mainly during disruptions and thus can be undervalued in stable periods. This uncertainty is amplified for SMEs, which may lack the capital and data science capacity to build and maintain digital twins. Consequently, recent Industry 5.0 roadmaps argue for phased adoption where early pilots produce measurable benefits and create internal capability before scaling.

6. Strategic Implementation Roadmap

Industry 5.0 implementation is best approached as a capability-building trajectory rather than a one-time transformation. The proposed roadmap decomposes adoption into three phases—foundation, integration, and optimization—each of which develops both technical infrastructure and socio-organizational practices. The logic is to first establish measurement and governance prerequisites (so that human-centricity and sustainability are measurable), then to integrate digital twins and HRC workflows (so that trade-offs can be simulated and managed), and finally to optimize through AI-driven closed-loop operation (so that the system learns and adapts over time). Table 1 summarizes this roadmap with expected artifacts and representative indicator sets.

The roadmap implies that managerial commitment is required not only for capital expenditure but for governance and capability development. First, measurement must be treated as a strategic asset: without reliable ergonomic, energy, and disruption indicators, Industry 5.0 remains rhetorical. Second, steering mechanisms should explicitly manage pillar trade-offs, for example through a cross-functional committee that include operations, safety, sustainability, IT/security, and workforce representatives. Third, adoption should prioritize transparency: operators must understand why a task allocation changes or why a schedule is adjusted for energy reasons. Finally, resilience planning should be institutionalized through regular scenario exercises and learning loops rather than ad hoc responses to crises.

Table 1. Phased Roadmap for Industry 5.0 Implementation with Measurable Indicators

Phase / Horizon	Integrated actions across the three pillars	Expected artifacts (technical + managerial)	Representative measurable indicators (examples)
Phase 1: Foundation (0–12 months)	Establish baseline measurement for safety, ergonomics, energy/carbon, and disruption response; select low-risk HRC pilots; build data pipelines and initial digital models; define governance for human data and AI assistance.	HRC risk assessment and SOPs; initial asset/process models; data governance policy; workforce training plan; edge connectivity assessment.	H: near-miss rate, ergonomic risk baseline; S: energy intensity baseline; R: time-to-detect (TTD) for disruptions; Governance: cybersecurity posture score.
Phase 2: Integration (12–24 months)	Deploy human–robot collaboration at scale in selected lines; implement digital twin(s) for process and energy; integrate sustainability constraints into planning; establish incident learning loops and human-in-the-loop decision rights.	Operational digital twin with what-if simulation; integrated HRC task allocation logic; sustainability dashboards tied to operations; cross-functional steering mechanism.	H: reduction in high-risk postures; S: carbon intensity per unit; R: time-to-respond (TTR) and recovery drills; Quality: scrap/rework rate.
Phase 3: Optimization (24+ months)	Enable closed-loop optimization via edge AI and analytics; integrate supply-chain twin for viability stress testing; adopt 6G/MEC where URLLC is required; scale personalization capabilities with governance and verification.	Closed-loop sense–simulate–decide–act–learn pipeline; resilience scenario library and playbooks; model validation/audit processes; continuous upskilling program.	**H**: sustained workload balance and acceptance; **S**: peak energy reduction and circularity rate; **R**: time-to-recover (TTRc) and viability margin; Financial: risk-adjusted ROI.

7. Future Research Directions

Several research directions appear especially consequential for the next wave of Industry 5.0 systems. First, trustworthy and verifiable AI for industrial decision making remains an open challenge. LLM-based interfaces promise to reduce the engineering barrier for robot programming and troubleshooting, yet their probabilistic nature and potential to generate incorrect outputs create safety and quality risks. Future work should therefore focus on grounded language models that integrate verified industrial knowledge bases, formal constraint checking, and runtime monitoring—so that recommendations can be audited and unsafe actions can be blocked. Recent surveys explicitly identify verification, domain grounding, and human-in-the-loop governance as prerequisites for deploying LLMs in Industry 5.0 settings.

Second, human digital twins require methodological advances that connect physiological and cognitive models with manufacturing control without creating surveillance harm. Research needs include: (i) privacy-preserving learning and inference for human-state estimation, (ii) uncertaintyaware ergonomic risk models that remain valid across diverse populations, and (iii) participatory governance methods that define acceptable uses of human data. The academic consensus is that HDTs could become a central enabler of human-centric optimization, but only if ethics and privacy are treated as system requirements rather than compliance afterthoughts.

Third, networking and computing research for Industry 5.0 must pursue determinism, sustainability, and semantics simultaneously. The URLLC and MEC are essential for time-critical collaboration, but the future challenge is to deliver these guarantees with low energy overhead. RIS-enabled smart radio environments are actively studied to shape propagation for reliability and efficiency, while THz links offer high capacity for sensing and digital twin synchronization at the cost of sensitivity to blockage and alignment. Semantic communication is another promising pathway because it can reduce network load by transmitting meaning relevant to tasks rather than raw data streams; recent surveys catalog architectures and applications that are likely to intersect with industrial digital twins and edge intelligence.

Fourth, optimization under deep uncertainty will become more central as climate-driven events and geopolitical disruptions increase. Digital twins and viability-based resilience metrics provide a platform for stress testing, but research is needed to integrate these analyses into real-time decision making. This includes robust and stochastic optimization methods that can be computed quickly at the edge and learning algorithms that can adapt when distribution shifts occur. Quantum computing is sometimes proposed for complex industrial optimization, but near-term value is more likely to come from hybrid methods that combine classical optimization, simulation, and learning within the closed-loop architecture.

Finally, policy and standardization remain critical. HRC safety practice is influenced by standards and regulations, and the emergence of LLM-driven autonomy and human digital twins will likely require updated guidance on responsibility, validation, and data rights. Future research should therefore include interdisciplinary work that connects engineering innovations with regulatory frameworks and human-centered design methodologies, ensuring that Industry 5.0 advances improve welfare rather than producing new forms of risk or inequity.

8. Conclusion

Industry 5.0 represents a paradigm shift from automation-as-goal to collaboration-as-goal. The transition requires more than adopting cobots, digital twins, or AI in isolation; it requires an explicit coupling of human-centricity, sustainability, and operational resilience through shared measurement, simulation, and governance mechanisms. This paper proposed a multi-dimensional framework that places an integration kernel—digital twins, AI analytics, edge–cloud networking, and governance—at the center of the three pillars, and articulated a closed-loop “sense–simulate–decide–act–learn” operating logic to make the framework deployable. The accompanying 6G-driven reference architecture illustrates why deterministic connectivity and edge intelligence are becoming foundational for safe and responsive human–machine collaboration. A phased roadmap was provided to translate the framework into actionable steps and measurable indicators.

The core implication is that Industry 5.0 should be managed as an interdisciplinary socio-technical transformation spanning engineering, operations management, sustainability science, and human factors. Future progress will depend on trustworthy AI, privacy-preserving human digital twins, sustainable edge intelligence, and resilience analytics that can operate under deep uncertainty. By treating humans, the planet, and continuity as first-class design objectives, Industry 5.0 offers a pathway toward factories that are not only efficient, but also humane, sustainable, and resilient.

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FROM VISION TO ACTION: THE EQUITY-OPERATIONAL SYSTEMS (OPS) FRAMEWORK FOR TRANSFORMING SCHOOLS THROUGH SOCIAL JUSTICE AND CULTURALLY RESPONSIVE LEADERSHIP

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Abstract

Schools continue to reproduce structural inequities that disproportionately affect historically marginalized students. Although social justice leadership (SJL) and culturally responsive leadership (CRL) frameworks have advanced equity-focused practice, they primarily address individual dimensions of equity rather than providing a unified operational system. This article presents Equity-Operational Systems (Equity-OPS) as a conceptual framework which positions equity as the central operating principle of school leadership rather than an add-on or a one-off initiative. By drawing on the synthesis of SJL, CRL, systems thinking, and transformative leadership, Equity-OPS comprises five interconnected components: Visionary Leadership, Systemic Transformation, Culturally Responsive Leadership Immersion (CRLI), Stakeholder Co-Leadership Networks (SCLN), and Equity-Based Accountability Contracts (EBAC). The primary contribution of this framework is the integration of these five components into a self-reinforcing cycle that institutionalizes equity across organizational systems. Although conceptual in nature, it has significant implications for educational practice, leadership preparation programs, and future research on equity-centered leadership.

Keywords: *Equity-Operational Systems; Educational Equity; Social Justice Leadership; Culturally Responsive Leadership; Equity-Centered Leadership*

1. Introduction

Educational equity has become a central focus of educational research and school policy. A growing body of research identifies school leadership as a key mechanism for advancing equity, improving student outcomes, and reducing achievement gaps. The field of SJL has moved toward designing more effective leadership preparation programs with an equity focus. These programs aim to equip aspiring school leaders with the knowledge, skills, and dispositions necessary to create inclusive and equitable learning environments.

In the U.S. context, where leadership preparation and development programs have been more deeply examined, we know that students attending schools led by principals trained in high-quality preparation programs see greater achievement gains and positive outcomes than students with principals from more conventional programs. (Richard & Cosner, 2024, p. 2)

The currently available preparation programs are not adequately preparing the next generation of educational leaders to become equity-centered leaders for all students. Richard and Cosner (2024) conducted an integrative review of program preparation for equity-focused leaders. Richard and Cosner (2024) identified four elements that need to be incorporated into a high-quality, equity-

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focused preparation program for school leaders: program vision, curriculum, pedagogy, and program assessment.

Based on recent research on SJL and education within Indigenous populations, Temiar and Jarvis (2024) argued that current conventional frameworks are inadequate to deal with the complex reality of marginalized students. The inequities in the education of Orang Asli in Malaysia, for example, are not only based on material reasons but also on cultural and epistemological reasons involving a combination of disadvantage and the misrecognition of Indigenous communities and their identities (Temiar & Jarvis, 2024). Research on SJL therefore advocates leadership approaches that are culturally responsive, contextually grounded, and developed in partnership with Indigenous communities. Temiar and Jarvis (2024) highlighted the importance of epistemological justice alongside redistribution and recognition. Addressing these inequalities requires collaborative, community-driven models of school leadership that engage Indigenous stakeholders in all levels of educational decision-making. These models should ensure the comprehensive involvement of all pertinent Indigenous stakeholders in every level of school decision-making and aim to enhance the relationships between schools and their communities (Temiar & Jarvis, 2024). SJL within Indigenous education is a complex and transformative process necessitating fundamental changes at the systemic level. Such transformation requires systemic reform, cultural validation, and integration of Indigenous knowledge into leadership practice.

Torrance and Forde (2017), in their scholarly work on SJL, contributed to the growing body of research in the field of equity-centered leadership. Torrance and Forde (2017) examined strategies for creating equitable schools that support diverse student populations. Their findings highlight the necessity for school leadership to move beyond technical school improvement efforts and address the broader social, cultural, and political contexts influencing schools. Torrance and Forde (2017) also highlighted that school leaders need to create schools that are equitable and characterized by inclusive practices. The research conducted by Torrance and Forde (2017) aligns with a wider body of literature that highlights the necessity for leadership strategies capable of identifying and addressing inequitable systems present within educational institutions.

The literature explains a variety of models of social justice leadership, culturally responsive leadership, and transformative leadership that address different dimensions of equity. However, such models approach equity separately or as one dimension rather than as an integrated organizational operating principle that must be a part of the entire school's operating system. Therefore, there is a need for a more comprehensive framework for addressing and embedding equity throughout a school's operations. This article describes the Equity-OPS framework for supporting educational leaders in developing schools that foster an equitable learning environment for all students.

2. Persistent Inequities in Education

Schools are part of the larger systems of broader society, and they reproduce and/or challenge the larger systems of social stratification. Consequently, schools may reproduce systemic inequities that contribute to persistent achievement gaps among historically marginalized students. Condron (2009) pointed out that educational inequality is associated with wider structural inequities. These inequities are reinforced through unequal access to resources and opportunities, as "poor and working-class students… achieve at lower levels… due largely to social class differences and inequities surrounding household educational resources" (Condron, 2009, p. 683). Additionally, school structure, policies, practices, and school culture tend to categorize students into groups. These groups of students are not categorized using the same criteria. Instead, specific criteria are used to label students of color, while other criteria are used to classify their White counterparts. Students of color are disproportionately placed in educational contexts associated with fewer opportunities, whereas White students more frequently benefit from structures that support academic success. Condron (2009) stated that “the broader structure of social stratification produces class and racial disparities in learning, and school reforms cannot eliminate achievement gaps as long as that stratification is left intact” (pp. 683-684). Students experience “categorically unequal and qualitatively different… life and educational experiences” (Condron, 2009, p. 685) depending on their rank in the social class hierarchy.

Condron (2009) further demonstrated that educational inequalities mirror broader patterns of racial and socioeconomic stratification. The author argued that despite the continued existence of social and economic structures of inequality between Black and White Americans, persistent and especially intractable inequalities exist within educational outcomes. “As social and economic stratification between Black and White Americans persists… disparities in educational outcomes remain an especially formidable barrier” (Condron, 2009, p. 683). Condron (2009) reported that “non-school factors primarily fuel black/white inequality in gains” (p. 698) and that “schools appear to exacerbate black/white disparities in learning” (p. 699). It has also been established that it is within the structures of schools that Black students are far more likely to attend minority segregated schools. These students do not often achieve gains in reading and math when compared to their peers who attend schools that are not predominantly minority schools. Racialized school segregation appears in the way that “black students… are far more likely to attend minority segregated schools” (Condron, 2009, p. 699), where “attending a predominantly minority school… inhibits both reading and math gains” (pp. 699-700). Condron (2009) clearly indicated that inequalities that are apparent within outside-school circumstances are also exacerbated by in-school structures. This is evident in the minimal achievement in reading and math for Black students in comparison to their White counterparts.

According to Theoharis (2007), one of the primary ways in which inequitable aspects of schools are reproduced is through issues such as school segregation and exclusionary school discipline practices. Students attending schools with a high percentage of students of color are more likely to attend schools with fewer resources and less support for academic success. These patterns of inequitable access to learning opportunities are consistent with more recent findings from the U.S. Department of Education, Office for Civil Rights (OCR, 2025). For example, although 48% of all public and private high schools in the country offered calculus, 61% offered physics, and 76% offered chemistry, more than 80% of high schools offered the foundational courses of Algebra II and biology. The data also show that Black and Latino students have unequal access to similar high-level courses as their White peers. For example, while 54% of high schools with low enrollments of Black and Latino students offered calculus, only 35% of high schools with high enrollments of Black and Latino students offered the same course. Similarly, 54% of high schools with low enrollments of Black and Latino students offered computer science courses, as opposed to 42% of high schools with high enrollments of Black and Latino students. These findings expose a persistent and even increasing pattern of inequality regarding whether marginalized students have access to the opportunities necessary to prepare them for college and careers. Collectively, these studies and statistics demonstrate that educational inequities are produced through the interaction of broader social conditions, organizational structures, and institutional practices.

3. The Evolution of Social Justice Leadership (SJL) as an Educational Leadership Paradigm

Building on the preceding discussions, recent academic publications have further clarified the current trajectory of the SJL. Traditional models and practices of SJL have sought to challenge and overcome systemic inequities to advocate for students marginalized by school policies and institutional practices (Theoharis, 2007). Studies on SJL posit that school leaders have moral responsibilities to ensure that all students succeed in school. However, recent work in Indigenous contexts extends this perspective by emphasizing that inequities are not solely structural but also cultural and epistemological. For example, Temiar and Jarvis (2024) demonstrated that educational inequities experienced by the Orang Asli community reflect both material disadvantage and cultural misrecognition. SJL in Indigenous settings requires leaders to confront deficit narratives and collaborate with communities to co-construct equitable educational environments. Thus, SJL is re-envisioned as a multidimensional and transformative framework that integrates structural change, cultural recognition, and epistemological validation.

Karakose et al. (2023) examined the intellectual progression of SJL in education by conducting a bibliometric study of 135 academic articles published between 2003 and 2022. The study identified three developmental stages of the field: SJL emergence (2003-2012), expansion (2013-2017), and maturation (2018-2022). Their findings indicate that SJL has evolved from a purely conceptual field of study to an outcome-oriented field of practice. The authors identified three core themes: "Social-Justice-and-Equity, Leadership, and Transformative-Leadership emerged as the motor themes that contributed the most to the field's development" (Karakose et al., 2023, p. 7) which shaped the development of SJL as a field of study over the years. The early phase of SJL established a moral foundation for leaders to address injustices and advocate for change. The findings showed that the ethical responsibilities of educational leaders could be facilitated by adopting transformative leadership approaches that promoted inclusive education, social change, and equity. Accordingly, the emergence phase emphasized how school leaders could manage and operate within structures and cultures of schools to challenge injustices.

The expansion phase (2013-2017) focused on leadership practices and how social justice values were put into practice within real-life educational contexts. Karakose et al. (2023) observed that research increasingly examined how leaders enacted inclusive policies, reformed inequitable practices, and fostered equitable school environments. During this phase, educational leaders implemented equity-oriented practices within the contexts of schools and districts. The expansion phase indicates that the field has progressed from conceptualization to practical implementation of social justice in education.

During the maturation phase (2018-2022), SJL studies began to focus on the measurable outcomes of leadership and its broader effects on schools and students. In line with these goals, the main themes of recent studies on SJL are school leadership, instructional leadership, well-being, equity, and LGBTQ (Karakose et al., 2023). Thus, SJL studies have moved from a single concept understood within a philosophical framework to a more integrated multidimensional structure to promote equity with educational outcomes and the socio-emotional development of students in schools.

Karakose et al. (2023) suggest that the field of SJL has moved from a theoretical approach to a more empirically informed and then an outcome-oriented field. This reflects the development of SJL as not only a morally driven endeavor that attempts to challenge and overcome educational inequities but also a field that focuses on developing best practices to bring about positive change for marginalized students and help them succeed in school. Simultaneously, the field links equity-focused educational leadership with the success of students from underprivileged backgrounds in academic and socio-emotional terms.

Recently, an increasing number of studies have begun to examine how issues of inequality are created and sustained not only by structural frameworks of schooling but also by cultural aspects.

Temiar and Jarvis (2024) explored how SJL in Indigenous communities can be adapted to transform schools from within. The authors suggest that SJL needs to expand its focus from structural change to epistemological and cultural transformation. They further argued that such practices must be grounded in community knowledge and participatory practices. Temiar and Jarvis (2024) presented the case of Orang Asli where Indigenous students challenged the fair recognition of their unique culture in the school setting. Temiar and Jarvis (2024) argued that effective SJL recognizes the limitations of generic practices of leadership for social justice. Temiar and Jarvis (2024) asserted that adapting the SJL for Indigenous communities requires a transformation of practices that are currently believed to be effective for promoting social justice change. According to Temiar and Jarvis (2024), the continued evolution of SJL necessitates leaders to address inequities not only through systemic restructuring but also through the assertion of cultural identities, epistemological justice, and authentic partnerships with marginalized communities.

4. The Equity-OPS Framework

The Equity-OPS framework addresses a significant gap in the literature by integrating school leadership and organizational management into a cohesive, operationalized system for equity centered leadership system. This framework is derived through a theory-driven synthesis integrating insights from SJL, systems thinking, equity-centered school improvement, and organizational change literature. There is an abundance of research on equity initiatives, professional development, community engagement, and policy reform. However, each of these elements has been examined in isolation and does not function as a unified, cohesive, operational system. This article proposes Equity-OPS as an operational framework for SJL that positions equity not as a discrete initiative but as the foundational operating principle through which schools function.

Table 1. Equity as Initiatives vs. Operating Principles

Equity as Initiative	Equity as Operating Principle
Equity is the responsibility of leadership.	Equity is the responsibility of all the stakeholders.
Equity work is typically seen as taking place at certain events or as part of specially designated times (e.g., staff meetings, professional development days).	Equity work is typically integrated into daily school operations.
Equity programs coexist with traditional systems	Equity fundamentally reshapes how systems function
Measuring success by the completion of equity initiatives ("Did we run the training this year?")	Measuring success by changes in outcomes that affect equity for students (Did disparities decrease for our students?)
Equity depends on the work of a few champions to keep it going; once the key people leave the school, the equity work goes with them.	Equity is institutionalized in the structures of a school; therefore, it persists even after leaders have left.

4.1. Visionary Leadership: Embedding Equity as the Central Organizational Logic

Visionary leadership anchors the Equity-OPS framework by positioning equity-centered decision-making as a foundational element for operating schools. Rather than treating equity as a program, add-on, or periodic initiative, school leaders cultivate teachers' understanding of how school practices differently affect student groups and intentionally redistribute resources to better support the academic success of all students.

Equity-centered leadership begins with a visionary approach. Here, school principals enact SJL by embedding equity as a central theme of the school's vision and mission. In this case, equity should be rooted in hiring, budgeting, and the public face that the school projects to the community through the stories that are told. Theoharis (2007) makes "issues of race, class, gender, disability, sexual orientation, and other historically and currently marginalizing conditions in the United States central to their advocacy, leadership practice, and vision" (p. 223). However, Theoharis (2007) predicts that this public stance can face resistance from staff, parents, and district administrators. According to Theoharis (2007), "resistance is predictable, but it should not be a barrier to refrain from the challenge for equity" (p. 237).

This visionary commitment guides leaders to explicitly name systemic inequity rather than simply celebrating diversity in the abstract. Thus, school leaders must go beyond recognizing and celebrating diversity to engage in deep reflection on the issues of power, privilege, and injustice. Shields and Hesbol (2019) reinforce this point, emphasizing that transformative leaders must go beyond surface-level inclusion and instead engage in "deep reflection on issues of power, privilege, and injustice" that shape students' educational experiences" (p. 5).

Furthermore, visionary leadership can motivate school leaders to collaborate to create systems that foster equitable learning opportunities for all students. An equity-centered leadership vision should extend to preparation programs that prepare school leaders for enacting SJL in schools. As Richard and Cosner (2024) explained, "a vision for a principal preparation program can support more intentional program design that begins with the end in mind" (p. 6). When the goal is equity, all elements of leadership preparation programs can be intentionally structured to develop leaders who are both prepared and dedicated to promoting social justice within their schools.

4.2. Systemic Transformation Through Equitable Resource Allocation and Inclusive Practices

The second phase of the Equity-OPS framework operationalizes the shift from visionary commitment to organizational redesign. This phase translates equity-centered leadership into systemic organizational change by redesigning resource allocation, instructional practices, and inclusive school structure. Theoharis (2007) reinforces the substantial role of educational leaders in attempting to achieve educational equity and confront deep-seated systemic inequities within and across schools over time. Schools are sites where structures and practices can work to include or exclude students and help or hinder learning for various groups. For example, schools serving high percentages of students of color often have curricula that are less challenging than those found in schools serving a greater percentage of White students (Condron, 2009). These disparities highlight the need for SJL who can promote more equitable educational environments. Theoharis (2007) suggests that leaders who are attempting to promote equity assist teachers in schools to view issues that might negatively impact unprivileged students. In this case, school leaders must promote practices and help redistribute resources to better support the academic success of all students.

Similarly, Shields and Hesbol (2019) describe how schools can be organized to support all students in achieving their goals. They suggest encouraging educators to question and challenge the persistent systems of inequality that affect all aspects of school life. Schools can become sites for transformation of broader social justice issues when leaders promote equity-oriented school policies and work to advocate on behalf of all students, especially those who have been historically marginalized. The work of SJL requires a commitment to dismantle structures of inequality and to take on difficult issues to create democratic school environments and to promote learning environments that support the development of all students. SJL has a challenging task to bring about the required change, and they need to be brave, ethical, and ready to work tirelessly. Creating an inclusive school environment is a key goal for SJL to redistribute resources to ensure that all students have access to quality instructional programs and opportunities for success.

4.3. Culturally Responsive Leadership Immersion (CRLI): Leveraging Culturally Diverse Assets

In this phase, CRLI operationalizes a more rigorous approach by moving beyond awareness-building to cognitive, emotional, and behavioral transformation through sustained, cultural experiential immersion. Klingner et al. (2005) describe "addressing the disproportionate representation of culturally and linguistically diverse students in special education through culturally responsive educational systems," noting that change requires "cutting across three interrelated domains: policies, practices, and people" (p. 1). Critically, this work cannot be done in isolation; it requires combining “responsive, evidence-based interventions and strategic improvements in practice" (Klinger et al., 2005, p.2).

Social justice leadership is closely linked to culturally responsive leadership. Rodriguez (2026) states that “Culturally Responsive Leadership Theory extends the principles of culturally relevant pedagogy into the domain of educational leadership by emphasizing equity, inclusion, and social justice” (p. 9053). CRL emphasizes recognizing, valuing, and leveraging the cultural knowledge students, families, and educators bring to schools to promote fairness and student success. It is a framework that can address the challenges that educational organizations face in their quest to prepare all students for future success. Rodriguez (2026) proposes CRL as a framework that is “capable of addressing these challenges by centering leadership practices on equity, inclusion, and cultural awareness” (p. 9050). For instance, school administrators can create collaborative structures such as professional learning communities to advance educational equity. Teachers can strengthen CRL by growing in their practice of culturally responsive pedagogy. Parents and guardians of students can support educational equity by maintaining communication with teachers and supporting school initiatives that promote issues of fairness in learning. “Recent research has positioned CRL as a reform-oriented and equity-centered practice that integrates culturally responsive pedagogy (CRP), social justice values, and authentic student and community-based voices” (Jumaah et al., 2026, P. 291).

Khalifa et al. (2016) expands the application of CRL by describing school leadership through the lens of caring for, challenging, and acting on behalf of marginalized populations and communities. Khalifa et al. (2016) transforms the conceptualization of CRL from being confined to school-based practices to include a focus on transforming relations and power dynamics between schools and communities. The two interconnected practices of maintaining high expectations and advocacy are central to the framework of CRL. By positioning high expectations as a non-negotiable practice in schools, Khalifa et al. (2016) reinforce the practice of “warm demanders” represented by researchers. The concept of “Warm demander” suggests that by combining cultural responsiveness and care with academic rigor, educators and school leaders can support student growth in school. Khalifa et al. (2016) suggest that “leaders embody this approach to relationship-building with students and communities. Although school leaders may on occasion criticize local student practices, embedding love and hope in school environments is a key practice for building positive school environments for learning” (p. 1295). Thus, Khalifa et al. (2016) extends the work of CRL from being a practice of individual school leaders to a collective practice that organizes the work of school leaders and informs a framework of school reform that is grounded in the values of care, equity, and social justice. Such work demands an equity-centered leadership that goes beyond the management model found in most schools and seeks to transform educational administration's focus into social justice and cultural responsiveness (Richard & Cosner, 2024).

4.4. Stakeholder Co-Leadership Networks (SCLN): Fostering Authentic Shared Leadership

Traditional approaches position schools as institutions that engage families or partners with communities as peripheral supporters. In this phase, Equity-OPS reconceptualize families and communities as co-leaders leaders of educational systems rather than auxiliaries to school leadership. SCLN operationalizes equity-centered Leadership by transforming schools from institutions that serve communities to institutions co-led by families and communities themselves.

Including marginalized voices in school governance decisions is not sufficient to deepen the CRL if power sharing is merely symbolic. According to Ishimaru (2018), families and community members can drive systemic changes when they function as educational community leaders. A significant component of Ishimaru's (2018) work is that he challenges the implicit hierarchy of professional school leaders who make decisions and invite community input while community leadership is not institutionalized. Sustaining community leadership within and across institutions requires a shift from dependent personal involvement to system leadership. This requires more than a handful of charismatic parents. SCLN can be facilitated through the development of formal embedded structures such as a leadership team, an advisory council, and community governance councils. This phase of Equity-OPS extends the role of families and communities to co-design and co-govern school initiatives as full members of a governing body. Ishimaru (2018) reported that "PTA parents explicitly refused the institutional scripts associated with the PTA regarding their role as passive supporters and "cookie-bakers" (p. 555). These structures institutionalize community leadership by creating enduring governance mechanisms that persist beyond individual participation.

DeMatthews et al. (2017) studied a group of superintendents to examine the implementation of dual language education along the US-Mexico border. Rather than making decisions for Latino emergent bilingual students' education, superintendents engaged with communities to define equitable education and how to achieve it. However, while communities were included in decision-making regarding education and resource inequities, underfunded programs restricted their long-term systemic change. DeMatthews et al. (2017) admit that while amplifying marginalized voices is critical to deepening the CRL through authentically structured community engagement, these efforts are for now fragile and limited in their transformative potential. SCLN can grow when authentic community engagement occurs while avoiding symbolic or tokenistic participation. SCLN empowers historically marginalized students by moving beyond tokenism to authentic community co-leadership.

4.5. Equity-Based Accountability Contracts (EBAC): Replacing Traditional Evaluation with Equity Contracts

In this phase, EBAC operationalizes the shift from traditional accountability models to a participatory and localized accountability system. EBAC replaces traditional evaluation with collaborative accountability agreements where teachers and leaders co-construct equity goals, define success, and commit to continuous improvement through professional learning rather than punishment. Instead of relying primarily on external evaluation, EBAC begins with teachers and leaders collaboratively defining equity goals specific to their context. Unlike top-down accountability, EBAC is participatory and context-specific.

Traditional accountability models, particularly those emerging from the "new public management" era, have created systems in which educators experience accountability as external punishment and compliance. Jakobsen et al. (2017) identified a fundamental mismatch between external accountability regimes and the inherent characteristics of public sector work. The authors argue that such regimes are often perceived as externally imposed mandates that foster passivity, gaming, and evasion rather than genuine improvement. Jakobsen et al. (2017) found that traditional "standards that encourage passivity, gaming, evasion, and will never be able to achieve performance gains that depend on purposeful professional engagement" (p. 2).

When accountability systems are punitive, threatening teachers with sanctions for low test scores, they undermine the trust essential for genuine improvement. Jakobsen et al. (2017) proposed an alternative: "internal learning (IL) regime" where "extensive professional involvement in the development and interpretation of goals" (p. 5) replaces external mandates, creating conditions in which "improvements depend on purposeful professional engagement."

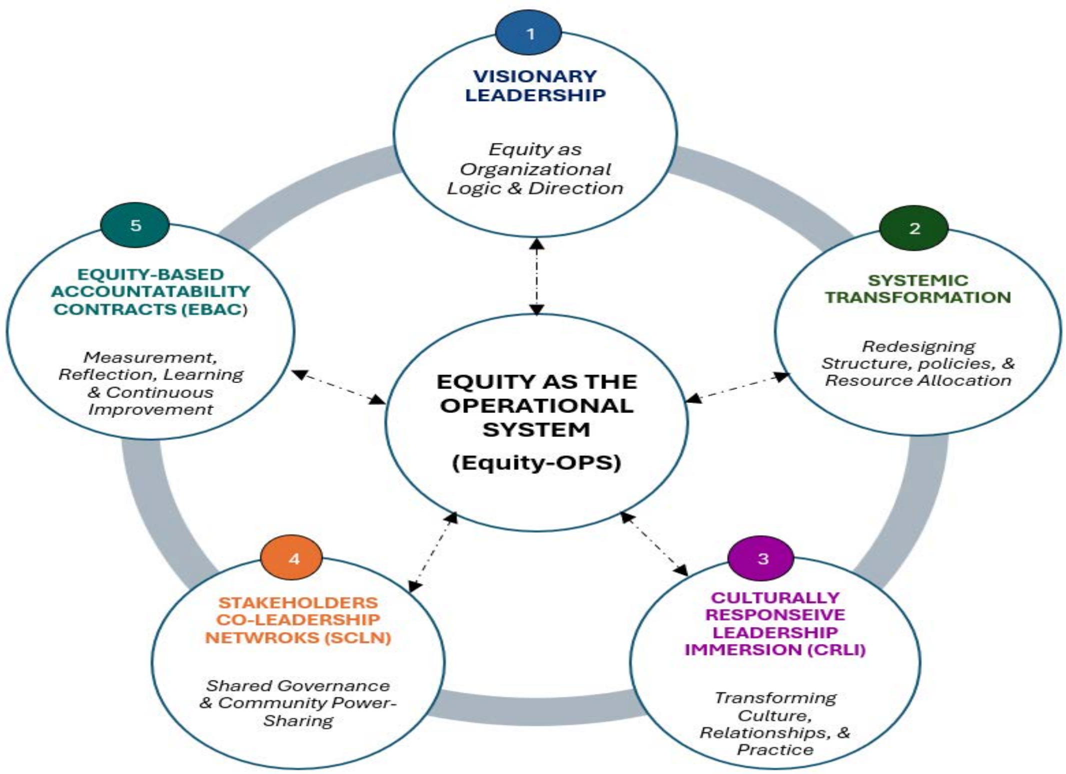

Figure 1. Equity-OPS Framework

5. Conclusion

Prior research on leadership for social justice and culturally responsive schools has established the moral imperative for developing schools that are truly equitable for all students (Karakose et al., 2023; Khalifa et al., 2016; Shields & Hesbol, 2019; Theoharis, 2007). This rich body of scholarship tends to address specific dimensions of equity leadership in relative isolation from one another. As shown in Figure 1, the Equity-OPS framework consists of five components: 1) Visionary Leadership, 2) Systemic Transformation, 3) Culturally Responsive Leadership Immersion, 4) Stakeholder Co-Leadership Networks, and 5) Equity-Based Accountability Contracts. The persistent and well-documented inequities in schools demand more than moral awareness or isolated reform efforts.

The Equity-OPS framework emphasizes the school improvement process as a cycle as opposed to a linear sequence of steps. Additionally, the framework holds all school stakeholders accountable for meeting the needs of all students to achieve the school's equity-focused vision.

This Equity-OPS framework makes three primary theoretical contributions to the fields of SJL and CRL. First, Equity-OPS moves beyond disposition to operationalization. That is, the framework asks not only what leaders should believe or value, but precisely how those values should be enacted across every system and structure of the school, from hiring and budgeting to governance and evaluation. Second, Equity-OPS institutionalizes community co-leadership as a structural feature of school governance through the SCLN component. The framework positions families and communities as co-architects of educational systems rather than invited participants. Third, Equity-OPS replaces punitive external accountability with EBAC. EBAC invites teachers and leaders to collectively define success, commit to continuous improvement, and generate evidence that renews the system's equity direction. In this way, Equity-OPS reframes accountability itself as a tool for equity rather than a mechanism of control.

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