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Research Article

A Practical Application of the Analytic Hierarchy Process and Integer Linear Programming for Fuzzy Front-End Project Selection

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Purpose. This study applies a novel approach that integrates AHP with integer linear programming (ILP), to address a gap in management literature regarding the need to consider both sustainability and COVID-19 impact on project selection, with a view to avoid implementation failures. *Design/Methodology/Approach*. A case study approach involving experts in semiconductor manufacturing was conducted, using the Delphi method, to determine weights of various criteria, including additional new criteria associated with both sustainability and COVID-19 issues considered in the selection decision for four candidate projects. *Findings*. Integrated results revealed two projects to be selected (projects 1 and 3). Whilst AHP results revealed more information about the ranking of all four projects, the ILP model results complemented the findings by indicating that 2 projects (projects 1 and 3) should be selected, taking account of not only resource constraints but also sustainability issues and customer behavior towards selected projects, influenced by COVID-19 impact. *Originality/Value*. The value lies in not only proposing a novel framework that integrates AHP with ILP but also adding to our understanding of the importance to incorporate both sustainability and COVID-19 impacts on semiconductor industry project selection, both of which have significance for the industry in terms of maximizing implementation success for selected projects.

1. Introduction

A critical appraisal of extant literature reveals four major streams, in the context of project selection. The first stream focuses on concept selection, also known as idea evaluation, in the front end of the innovation process [1–5]. The second stream of literature demonstrates applications of the analytic hierarchy process (developed by Saaty) in project selection [1, 6–8], for different industries such as IT (information systems) [9], energy [10], computing and automation [11], and research and development [12]. The third stream emphasizes the use of mathematical models [13–15] in the context of decision-support tools to solve project selection problems. Some of the studies in the third stream specifically cover applications of linear and/or integer linear programming [16], goal programming [17], and other heuristic approaches such as branch and cut [15] whilst others use spreadsheet modeling concepts [18]. The last stream provides additional insights by either integrating [17] or comparing [19] more than two approaches to project selection, with a view to address a gap in previous studies associated with AHP's inability to take account of resource constraints in selecting the best projects among competing alternatives.

There is a growing body of literature on the impact of the COVID-19 pandemic on different industries, which should not be overlooked in project selection. For example, whilst Brown et al. [20] and Fransman [21] rightfully highlight the need for collaboration in the innovation of new products and services in terms of organizational competitiveness, they do not incorporate the context of the possible changes in customer's consumption of that product and services, arising from the impact of COVID-19. Furthermore, the growing body of literature on COVID-19 impact focuses primarily on the need for transformation in the eyes of internal organizational processes and/or approaches to work [22–25] and little on consideration of the behavior of an organization's customers, in the context of their decision to purchase products and services in the COVID-19 era.

1.1. Gap and Study Motivations. Whilst all the studies within the four major streams, as well as the growing body of literature on COVID-19 impact on industries, have contributed significantly to either how industries may better respond to the consequences of the COVID-19 pandemic and more specifically to project selection, what appears to be missing is the use of multimethodologies that address not only sustainability issues and the impact of COVID-19 pandemic on semiconductor industry but also implications relating to implementation failures for selected new product development projects.

A previous study [11] developed a novel and integrated framework for fuzzy front-end project selection, in the context of identified criteria for project selection via the Delphi method involving experts across seven world-class high-tech organizations from various countries. A total of 6 criteria and 22 subcriteria were identified by integrating three decision-making perspectives (reflections, intuition, and rationality), to address a research gap in existing studies concerning the use of one or two perspectives. The current study focuses on the practical application of the developed framework from a previous study [11], using both AHP and ILP to evaluate projects for a real-life case study. The practical application for the present study involves building on extant innovation management literature and drawing from a growing body of literature on the impact of COVID-19, to address the identified gap relating to the need for a new project selection framework that addresses not only sustainability issues such as economic, social, and environmental performance indicators [26, 27] but also consideration of implementation success factors for selected new projects, particularly in the context of the impact of COVID-19 pandemic on the semiconductor industry.

Motivated by these gaps, the aim of this study is to propose and apply a new project selection framework that integrates not only three decision-making perspectives but also concepts of the Analytic Hierarchy Process (AHP) combined with Integer Linear Programming (ILP), to add to a deeper understanding of the importance of combining both sustainability issues and COVID-19 impacts on new product development (NPD) project selection decisions in the manufacture of semiconductor chips, both of which have value for the industry in terms of implementation success.

The contribution from the current study is threefold: (1) applying an integrated AHP-ILP model to aid real-life project selection for a specific case study, (2) incorporating both sustainability issues and COVID-19 impact on project selection, and (3) addressing implementation success factors for new and selected projects.

1.2. Scope and Objectives. This study is concerned with the practical application of a developed framework for project selection, with a view to aid evaluation decisions for new projects to be funded in a specific case organization. The study is confined to a single case study in the manufacture of semiconductors and stakeholders within the business functions of product development, manufacturing, and engineering.

The specific objectives were (1) apply AHP in practice, for project selection, (2) formulate an ILP model for project selection, and (3) implement the ILP formulation in optimization software.

2. Literature Review

2.1. Project Selection. Innovation management literature reveals that project selection is made up of four phases, namely, selection, analysis, rating, and release authorization [2, 28–31]. Usually, a project selection team meets to select the potential new product project from the idea parking lot, in order required to balance the pipeline [29]. The concept of an idea parking lot refers to potential new project ideas that have been collected at the beginning of the NPD process and have gone through clarification and incubation of the then raw ideas. The idea parking lot may contain some of the project ideas that have not been approved (during release authorization) and hence returned to the idea parking lot to await another phase of release authorization, often at a later time [29]. The team then reviews the selected ideas and analyses and rates selected ideas on the basis of importance and alignment with the organizations' strategic goals. The ideas are ultimately approved or rejected. In case of an approval decision, the new project idea is either terminated or returned to the idea parking lot, in which case it will undergo another evaluation process at a later time [29].

The project selection team involved in the evaluation process requires increasing assistance in selecting the most viable new product idea, as the number of competing alternatives increases with decreasing time available to do the evaluation. The decrease in time can be attributed to an increasingly competitive market place, which calls for organizations to produce more and more innovative products required for maintaining sustainable competitive advantage in the marketplace [2, 28–31].

2.2. Multicriteria Decision Making Methods. A comprehensive review of literature on multicriteria decision-making (MCDM) methods including problem areas [32–58] revealed that MCDM methods can be categorized into two types, namely, multiobjective decision-making (MODM) and multiattribute decision-making (MADM). Whilst MODM methods involve decision problems where the solution space is continuous, MADM methods involve decision problems where the solution space is discrete. MADM is characterized by a predetermined set of decision alternatives [44] and suits the context of this study, given that the alternatives are predetermined and can take the form of discrete values. For example, the candidate projects to be evaluated in terms of selection are predetermined and can take the form of binary variables, which assume two values, namely, 1 (the project is selected) and 0 (the project is not selected).

The literature also reveals that MCDM methods for solving multicriteria decision-making problems are diverse and include AHP, ANP, Fuzzy Sets, TOPSIS, PROMETHEE, ELECTRE, WASPAS, VIKOR, ASPID, and MULTIMOORA [32–58]. However, the most commonly used MCDM methods are the analytic hierarchy process (AHP), ELECTRE, and TOPSIS (ibid). On the basis of both theoretical and practical viewpoints, AHP is equally as valid as the other methods [45]. A study [46] involving the principle of these methods concluded that although each method is different, they are both valid. However, several studies [47–49, 59] assert that people have found AHP to be more insightful since it provides a vibrant and formal structuring of the decision problem, to enable easy capturing of human perceptions. Furthermore, other studies [47, 50] are unified in concluding that AHP is a superior method of measuring human perception. In particular, AHP is the most popular approach for selection problems, especially when combined with other methods such as linear programming and goal programming [51, 52]. For these reasons, AHP was used in this study not only to help visualize the decision hierarchy for the project selection problem but also to integrate it with integer linear programming (ILP).

Besides the diversity of MCDM methods, a common denominator for the majority of them lies in the notion of alternatives and decision criteria [44]. A common classification scheme for MCDM techniques is on the basis of (1) data types (e.g., deterministic or stochastic) and (2) the number of decision-makers involved in the decision process. There are two critical steps in dealing with any MCDM problem, namely, (1) define the problem and (2) estimate the relevant data required to solve the problem [44, 45]. These steps are briefly discussed.

2.3. Define the Problem. Defining the problem entails both full understanding and formulation of the decision problem, in relation to the information required to inform decision-making [44, 45, 53–58]. Problem definition requires input from experts, to ensure correct definition, given that this step may be *"more relevant to the art than the science of MCDM"* [44]. This argument implies the importance of understanding the context under which the decision is made.

2.4. Estimate the Relevant Data Required to Solve the Problem. Given the need but difficulty of accurately estimating the required data, Triantaphyllou (2000) acknowledges the challenge involved in this step by stating *"it is difficult, if not impossible, to quantify"* (p. 23) qualitative attributes, which explains why *"many decision-making methods attempt to determine the relative importance, or weight, of the alternatives in terms of each criterion in a given MCDM problem."* This statement implies that it is easier to quantify the data required to solve an MCDM problem in relative terms rather than absolute terms, particularly if the data involve qualitative attributes that are often intangible. The assumption is that a decision maker can express his/her opinion regarding the performance of each individual alternative, with respect to each alternative.

2.5. Methods for Determining Criteria Weights and Evaluating Alternative Solutions. There are numerous methods for determining criteria weights and evaluating alternative solutions associated with multicriteria decision-making problems. The methods in the first set may be categorized into either direct or indirect determination of criteria weights [8, 10]. Examples of direct methods include scoring and metfessel methods. Examples of indirect methods include pairwise comparisons and fuller triangles. NewProd and the Analytic Hierarchy Process [59] fall under indirect methods [59, 60].

The methods in the second set may be categorized into four groups based on the following: (1) the presence of cardinal level information on criteria preferences, (2) the presence of ordinal level information on criteria preferences, (3) the presence of aspirational level information on criteria preferences, and (4) absence of information on criteria preferences [8, 10]. Examples of the methods in this second set include pairwise comparisons [59], which involve cardinal level information on criteria preferences.

2.6. Mathematical Modelling. In the context of a global industry classification standpoint, the literature on mathematical modeling reveals its application in numerous industries and examples [61, 62]. Mathematical modeling falls under optimization-based approaches that lead to an optimized and less subjective decisio since it takes account of a comprehensive range of variables (decision criteria) seamlessly and simultaneously [13, 63, 64]. It involves quantifying this comprehensive range of decision criteria in a standardized and consistent manner, thereby yielding improved accuracy in a timely manner [62]; [14, 15, 65]. This formal approach is suitable for use with other approaches, in the context of a robust solution to a multicriteria decision-making problem.

Mathematical models, as an optimization modelling technique, can be classified into three categories, namely, linear programming (LP), nonlinear programming (NLP), and goal programming (GP). LP and NLP apply to modeling problems in which the objective function and constraints can be expressed as linear combinations of the decision variables, while GP applies to problems in which the objective function and constraints cannot be expressed as linear combinations of the decision variables [16, 18, 62]. GP is suited to solving problems comprising more than one goal [18], which does not suit the purpose of this study involved with one goal (selecting the best project to fund among competing alternatives).

2.7. Critique of Extant Literature and Gaps. There are three perspectives to decision making that underpin the project selection process in the fuzzy front end of innovation. These are managerial intuition, rational decision making, and careful reflections [11]. The majority of existing studies focus on the first perspective, which in turn is predominantly used in practice by experts. However, a few studies have highlighted the importance of combining two perspectives, intuition and rationality. A previous study [11] has extended the understanding of existing knowledge on fuzzy front-end project selection by incorporating all three perspectives, in relation to a more robust outcome.

A critical appraisal of existing innovation management literature and applications of both AHP and mathematical models reveal significant contributions to aiding project selection decisions. The literature was categorized into three streams, namely, (1) concept selection in the front end of innovation [1–3, 5]; (2) AHP applications in project selection [6–8, 10–12]; (3) applications of mathematical models as decision support systems for project selection, using various modelling techniques such as linear programming, goal programming, and branch and bound [13–18, 64]. However, this study builds on existing literature by drawing from the emerging body of literature on not only the impact of the COVID-19 pandemic on organizations [22, 66, 67] but rather how the organization's customers will respond to new product introductions. Therefore, this study not only incorporates traditional key criteria for fuzzy front-end project selection, using AHP and mathematical modeling, but also key criteria relating to sustainability issues [20, 21] for selected projects and how COVID-19 influences customers' buying culture [23–25] for implemented new projects. The need to consider the impact of COVID-19 is substantiated by its disruptions to high-technology organizations that either led to delays in planned new product introductions or complete plant shutdowns [22, 67].

The need to draw from several literatures steams and bring them to bear on the proposed novel approach for the project is crucial to reflect the reality of the business environment as it relates to selection criteria that incorporate all important factors, to avoid implementation failures for selected projects. Therefore, an opportunity exists to propose a complementary and robust approach that addresses this gap, in addition to unlocking the potential value in revealing deeper insights related to a balanced and comprehensive understanding of how and why certain projects should be selected and not selected, in the presence of today's business constraints that include COVID-19 pandemic impacts to high-technology organizations.

3. Materials and Methods

This study was conducted using a practical application of both AHP and ILP as a basis for the research framework. Questionnaire surveys for each method (AHP and ILP) were used to solicit input from 15 experts pertaining to weights for all variables of interest. Three new additions were added to the variables of interest in existing innovation management literature pertaining to project selection, as discussed in sections 1 and 2.3. These additions were (1) the implementation success of each candidate's new project, (2) the influence of COVID-19 on customer behavior, given the discussion in section 2.3 relating to disruptions on high-technology product introductions, and (3) sustainability issues for selected new projects. These new additions are part of addressing the identified gaps discussed in section 1.

For AHP methodology, the survey setup started with a brief background about hierarchical structuring of the decision problem associated with the goal of selecting the best project by conducting pairwise comparisons of various criteria and decision alternatives or candidate projects, using Saaty's 1–9 scale for measuring experts' judgments [59] whilst a number of scales exist for comparing two elements/alternatives such as asymptotical [12], linear [59], logarithmic [68], geometric [69]. Saaty's 1–9 linear scale [59] was chosen because it is based on a ratio scale (as opposed to methods that use an interval scale) that suits the comparison between two pairs of elements/alternatives at a time, without the need for units [70]. The absence of units but rather relative weights allows experts to provide judgments (estimated) with some level of certainty, given familiarity with ratios in their day-to-day lives.

An example pairwise comparison was provided to the experts, along with definitions of each criterion for better understanding of the survey. Internal inconsistencies and group disagreements among the experts were then computed in relation to ensuring consistency indices. The pairwise comparison results were then synthesized into final weights by use of PCM software to compute the final rankings of the decision alternatives.

Conversely, for the ILP model, the study design started with mathematical modeling of the same decision problem in terms of linear programming formulation (decision variables, objective function, and constraints). The addition to AHP lies in the incorporation of constraints associated with project selection, which include resource constraints. The ILP formulation was then implemented into an optimization software (OpenSolver), which involved quantification of parameters and then running the algorithm (using the simplex method) to yield an optimum solution concerning which projects should be selected and which projects should not be selected without violating constraints conditions as per reality of the business environment. The research framework is depicted in Table 1.

3.1. Justification for AHP. AHP stands out for the following reasons [8, 10, 71, 72]:

(i) Ease of application to the nature of the problem
(ii) Intuitive nature of managerial decision-making (which enables creativity) suits AHP modeling (decision problem structure)
(iii) Use of verbal judgments for comparison, followed by verification of consistencies/inconsistencies in measurements
(iv) Superior in situations where the alternative solutions have a similar likelihood of success since it can still determine which solution to choose
(v) Ability to account for other important criteria, which enables customization to organizations

Table 1: Research framework.

Methods	
Analytic hierarchy process (AHP)	Integer linear programming (ILP)
Literature review and gaps	Literature review and gaps
AHP modelling: structure decision problem/setup AHP hierarchy	LP modelling: apply in form of ILP model (notation and formulation), quantify ILP model parameters, use as input data to model
Verify with industry experts (structure + content)	Validate with industry experts (ILP model variables)
Pairwise comparisons (eigen value method, 1–9 linear scale), using Delphi (participatory approach)	Implement ILP model formulation in optimization software, using real data from case organization
Check consistency indices (verify) and validate	Get ILP model output
Final ranking of projects (decision alternatives)	Selected and nonselected projects (decision alternatives), using binary variables

However, the limitation in the use of AHP on its own is acknowledged in relation to rank reversal [73, 74]. This implies that AHP is subject to preference reversal issues and hence prone to recommending a different decision solution in a case where a nonpreferred alternative is added to the list of alternatives.

3.2. AHP Modelling: Hierarchical Structuring of Problem. A four-level hierarchy comprising the goal of selecting the best project was implemented, using modifications of a developed and validated idea screening criteria [11]. The modifications were based on the need to incorporate: (1) the implementation success of each new project, (2) COVID-19 impact on customer behavior, and (3) sustainability issues. The AHP hierarchy was applied in practice, to evaluate 4 candidate projects as depicted in Table 2. Three new additions were made to the proposed framework in (Seboni, 2021), following broadening and drawing from literature on COVID-19 impact and sustainability issues in relation to implementation success for selected projects.

Five experts from the case organization, with in-depth knowledge and experience in manufacturing, engineering, and marketing-related issues associated with four candidate projects were used. The case organization is among the leading high-technology firms that manufacture components for electronic devices across the world.

3.3. Justification for LP. Among optimization modelling techniques, linear programming was chosen on the basis of its popularity for solving optimization problems such as project selection, where both the objective function and constraints can be expressed as linear combinations of the decision variables [16, 18]. In particular, integer linear programming (ILP), which is an advancement of linear programming, is more suited to the project selection problem in this study. The reason is that projects to be selected for funding are integers (and not fractions) and can better be addressed using ILP, which confines some or all of the decision variables to integer values.

3.4. ILP Model Formulation and Assumptions. The ILP formulation is summarized as follows, where k is the goal of selecting the best projects to fund, i is the projects, j is the decision criteria, and T is the time:

$$\text{Maximize} \sum_{i=1}^{m}\sum_{j=1}^{o}\sum_{k=1}^{q}\left(l_{ijk} \quad g_{ij} \quad c_k \quad I_i \quad F_{ij} \right) \text{Implementation success,}$$

Subject to:

$$\text{Time availability of decision maker: } \sum_{j=1}^{p} d_{ij}A_{ij} + p_i \leq T_i,$$

$$\text{Total number of projects for evaluation: } N_i = \sum_{j=1}^{p} F_{ij} + n_i \forall I,$$

$$\text{Maximum number of projects for funding cycle: } \sum_{j=1}^{p} F_{ij} + G_i \leq M_i \forall I,$$

$$\text{Special projects: } F_{ij} = 1, \text{where } j\varepsilon\,[\text{Special projects}],$$

Table 2: Hierarchical structuring of project selection decision problem.

Level 1 Goal	Level 2 Main criteria (4)	Level 3 Subcriteria (16)	Level 4 Alternatives
Select the best project among competing alternatives	C1: technological fit	C11: product advantage C12: design quality C13: manufacturing technology **C14: success probability and implementation success**	Project 1
	C2: marketing fit	C21: implementation difficulty C22: timeline C23: fit with existing distribution channels C24: growth opportunity **C25: customer behavior given COVID-19 impact**	Project 2
	C3: overall uncertainty	C31: mitigatable % loss C32: mitigatable uncertainty C33: market size C34: market growth	Project 3
	C4: total risk profile	C41: NPV payoffs ($) C42: NPV costs ($) C43: return on investment C44: required resources **C45: sustainability**	
C5: regulatory requirements		C51: environmental requirements C52: energy saving	Project 4
C6: existence and quality of protocol		C61: product development C62: fit with customer need C63: gap in product offering C64: nonrecurring engineering	

The subcriteria in bold font represents new additions in terms of contributions to existing literature.

$$\begin{aligned}
&\text{Only one budget per project: } \sum_{i=1}^{m} F_{ij} \le 1 \forall j,\\
&\text{COVID} - 19 \text{ impact on customer behaviour: } \sum_{i=1}^{0} C_{ij} \le 1 \forall j,\\
&\text{Sustainability: } \sum_{i=1}^{n} S_i = 1 \forall i,\\
&\text{No unallocated budget: } \sum_{j=1}^{p} F_{ij} \le 1 \forall i,\\
&\text{Binary variables: } F_{ij} = 0, 1.
\end{aligned} \tag{1}$$

The following assumptions were made in the formulation:

(i) All model parameters are deterministic

(ii) The experts can provide judgments using relative terms, hence ratios (no units)

(iii) Evaluations of decision elements are made at an explicit time

4. Results and Discussion

The results are presented in terms of the following: (1) profile of informants, (2) findings for separate AHP-ILP results, (3) findings for integrated AHP-ILP results, and (4) implementation steps for the proposed decision-making framework.

4.1. Profile of Informants. Data were collected from a panel of 15 experts with the following attributes: 3 out of 15 (20%) had doctoral degrees and numerous journal publications in fuzzy front-end project selection. All 15 (100%) had minimum 10 years' experience in evaluating projects for funding. These attributes demonstrate profile of informants, in the context of ability to give useful insights about issues concerning project selection.

4.2. Findings from Separate AHP-ILP Results and Integrated AHP-ILP Results. The optimal solutions for both independent AHP and ILP model results and integrated AHP-ILP model results are summarized in Table 3.

Firstly, the results from AHP methodology show that the sum of scores for each project is given by 0.27 (project

Table 3: Separate AHP-ILP model results and integrated AHP-ILP model results.

AHP results	ILP model results (optimal solutions)	AHP-ILP integrated results
$P1 = 0.27$ (rank 1)	$P1$ is selected, objective value = 789,911	$P1$ is selected
$P2 = 0.25$ (rank 3)	$P2$ is not selected	$P2$ is not selected
$P3 = 0.26$ (rank 2)	$P3$ is selected, objective value = 782,012	$P3$ is selected
$P4 = 0.22$ (rank 4)	$P4$ is not selected	$P4$ is not selected

(1) + 0.25 (project (2) + 0.26 (project (3) +0.22 (project (4) = 1 (where 1 represents 100%), consistent with multiattribute utility theory [75]. Secondly, these AHP results indicate that project 1 (rank (1) is the best to be selected for funding, followed by projects 3 (rank 2), 2 (rank 3), and 4 (rank 4). Conversely, the ILP model results, which complement AHP results by incorporating resource constraints to reflect the reality of the business environment, indicate that project 1 (where $i = 1,2,3,4$) should be selected for funding, followed by project 3 which has a lower objective function value than project 1.

This optimal ILP model solution satisfies all the constraints because it ensures, for example, that the entire budget is used up but not exceeded in consideration of the maximum number of projects to be funded and the time availability of experts in evaluating projects. An optimal solution means that the goal (where k = goal) of selecting the best projects (with higher objective function values) to fund is achieved, whilst satisfying all applicable constraints, unlike AHP on its own.

Whilst AHP results show more information concerning the ranking of each project, the ILP model results only show that 2 projects (projects 1 and 3) should be selected and 2 (projects 2 and 4) not be selected, without violating applicable constraints associated with project selection. Overall, both sets of results is consistent in the context of selecting the best 2 projects (project 1 followed by project 3, based on differences in the objective values). The integrated AHP-ILP results add value because they lead to an optimum selection decision that is more convincing in terms of avoiding underutilization or over-utilization of resources. It is interesting to note that the difference in the objective values for the selected projects, using the ILP model which takes account of additional factors associated with constraints that reflect reality, is 1% (789,911–782,012/789,911 *100). Similarly, the difference in the ranking of the same projects using AHP methodology is 1% (0.27–0.26).

4.3. Implementation Steps for the Proposed Decision-Making Framework. The implementation steps for the proposed framework to aid project selection decisions are as follows:

Step 1. Identify criteria (and subcriteria) for project selection (see Seboni, 2021) pullstop.

Step 2. Rank identified criteria (and subcriteria) pullstop.

Step 3. Obtain matrix for the relative contribution of projects with respect to criteria pullstop.

Step 4. Obtain matrix for relative contribution of criteria with respect to organizational goals pullstop.

Step 5. Determine the relative contribution of each project with respect to each organizational goal (product of steps 3 and 4) pullstop.

Step 6. Develop a mathematical model (ILP formulation) pullstop.

Step 7. Implement the model formulation in an optimization software of choice pullstop.

Step 8. Interpret model results and compare with results from steps 5 (AHP results) pullstop.

5. Conclusions

Traditional approaches to fuzzy front-end project selection have focussed predominantly on the use of AHP and mathematical models. This study builds on existing studies by drawing from not only innovation management literature but also emerging literature on COVID-19 impact on high-technology organizations, as new additions to address the need for incorporating the changing nature of customer's purchase decisions on new product introductions, along with sustainability issues and implementation success factors for selected projects. These new additions were brought to bear on an integrated AHP-ILP model that was applied in practice, to aid idea screening decisions pertaining to four candidate projects.

The contribution of this study is threefold: (1) application of an integrated AHP-ILP model to aid project selection using a real-life case study, (2) incorporation of both sustainability issues and COVID-19 impact on project selection, and (3) addressing implementation success factors for new projects, with a view to avoid implementation failures for selected new projects. The novelty of study also lies in the results from ILP complementing those from AHP, in the context of triangulation to avoid significant financial losses arising from funding projects with high likelihood of implementation failures. Whist existing studies have contributed to the application of AHP and ILP, this study uses a framework that considers three decision-making perspectives (reflections, intuition, and rationality) and applies it in practice to aid project selection decisions, by drawing from additional literature on both COVID-19 impact and sustainability in the context of maximizing project implementation success and hence minimizing project implementation failures.

5.1. Managerial implications. The findings from this study demonstrate compelling empirical evidence of the potential value to be gained by practitioners in terms of improving the effectiveness of their project selection, owing to new additions to the existing body of knowledge. These additions unlock the value to high-technology industry practitioners, in the context of revealing deeper insights related to a balanced and comprehensive understanding of how and why certain projects should or should not be selected, in the presence of recent business constraints influenced by the COVID-19 pandemic.

5.2. Limitations and Future Research. The use of five experts in validating AHP results may be viewed as a limitation. It should be noted, however, that studies on AHP applications [71, 76-79] reveal that a minimum of five key decision-makers in one major company is sufficient to validate AHP results. Another limitation of the mathematical model results lies in that, unlike AHP methodology, there is no explicit ranking of the 4 projects but rather, an indication of which specific projects must be selected for funding, on the basis of their respective objective function values. The use of binary variables means that projects are either selected or not selected, taking into account all the important decision criteria as per the AHP methodology.

An avenue for future research is to test the proposed complementary AHP-ILP approach to changes in the competitive landscape that affect which new project gets selected for further development. Another avenue for future research could include the use of SWOT analysis as an alternative method to be combined with AHP. It would be interesting to compare the SWOT analysis results with AHP results, in relation to verifying the final ranking of each project.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest concerning the publication of this paper.

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References

[1] Z. Ayağ and R. G. Özdemir, "A hybrid approach to concept selection through fuzzy analytic network process," *Computers & Industrial Engineering*, vol. 56, no. 1, pp. 368–379, 2009.

[2] R. G. Cooper, "An empirically derived new product project selection model," *IEEE Transactions on Engineering Management*, vol. 28, no. 3, pp. 54–61, 1981.

[3] M. Dziallas, "How to evaluate innovative ideas and concepts at the front-end?: a frontend perspective of the automotive innovation process," *Journal of Business Research*, vol. 110, no. 1, pp. 502–518, 2020.

[4] A. Sukhov, "The role of perceived comprehension in idea evaluation," *Creativity and Innovation Management*, vol. 27, no. 2, pp. 183–195, 2018.

[5] A. Kengpol and C. O'Brien, "The development of a decision support tool for the selection of advanced technology to achieve rapid product development," *International Journal of Production Economics*, vol. 69, no. 2, pp. 177–191, 2001.

[6] V. S. Lai, B. K. Wong, and W. Cheung, "Group decision making in a multiple criteria environment: a case using the AHP in software selection," *European Journal of Operational Research*, vol. 137, no. 1, pp. 134–144, 2002.

[7] E. W. T. Ngai, "Selection of web sites for online advertising using the AHP," *Information & Management*, vol. 40, no. 4, pp. 233–242, 2003.

[8] A. Siekelova, I. Podhorska, and J. J. Imppola, "Analytic Hierarchy Process in Multiple–Criteria Decision–Making: A Model Example," in *Proceedings of the SHS Web of Conferences*, Article ID 01019, Sanya, China, 2021.

[9] K. Muralidhar, R. Santhanam, and R. L. Wilson, "Using the analytic hierarchy process for information system project selection," *Information & Management*, vol. 18, no. 2, pp. 87–95, 1990.

[10] C. B. Si, R. Q. Wang, Y. S. Liu, S. Guo, Y. Yue, and J. Ren, Multi-criteria comprehensive energy efficiency assessment based on fuzzy-AHP method: A case study of post-treatment technologies for coal-fired units," *Energy*, vol. 200, pp. 159–172, 2020.

[11] L. Seboni, "A framework for identifying and validating idea screening criteria – a case of research and development projects in the computing and automation industry," *IEEE Transactions on Engineering Management*, pp. 1–10, 2022.

[12] F. J. Dodd and H. A. Donegan, "Comparison of prioritization techniques using inter-hierarchy mappings," *Journal of the Operational Research Society*, vol. 46, no. 4, pp. 492–498, 1995.

[13] M. M. Meerschaert, *Mathematical Modeling*, Elsevier/Academic Press, Cambridge, MA, USA, 3rd ed edition, 2007.

[14] J. Berry and K. Houston, *Mathematical Modelling*, Edward Arnold, London, 1995.

[15] D. Edwards and M. Hamson, *Guide to Mathematical Modelling*, Palgrave, London, UK, Second ed edition, 2001.

[16] B. E. Cushing, "The application potential of integer programming," *Journal of Business*, vol. 43, no. 4, pp. 457–467, 1970.

[17] M. J. Schniederjans and R. L. Wilson, "Using the analytic hierarchy process and goal programming for information system project selection," *Information & Management*, vol. 20, no. 5, pp. 333–342, 1991.

[18] C. T. Ragsdale, *Spreadsheet Modeling and Decision Analysis: A Practical Introduction to Business Analytics*, Cengage Learning, Boston, MA, USA, 7th ed edition, 2015.

[19] G. Noci and G. Toletti, "Selecting quality-based programmes in small firms: a comparison between the fuzzy linguistic approach and the analytic hierarchy process," *International Journal of Production Economics*, vol. 67, no. 2, pp. 113–133, 2000.

[20] P. Brown, N. Bocken, and R. Balkenende, "How do companies collaborate for circular oriented innovation?" *Sustainability*, vol. 12, no. 4, pp. 1–21, 2020.

[21] M. Fransman, *Innovation Ecosystems: Increasing Competitiveness*, Cambridge Univ. Press, Cambridge, UK, 2018.

[22] Z. Xu, A. Elomri, L. Kerbache, and A. El Omri, "Impacts of COVID-19 on global supply chains: facts and perspectives,"

IEEE Engineering Management Review, vol. 48, no. 3, pp. 153–166, 2020.

[23] P. W. Smith, K. Hansen, L. Spanbauer, and D. F. Shell, "Pandemic influenza preparedness: a survey of businesses," *American Journal of Infection Control*, vol. 35, no. 7, pp. 484-485, 2007.

[24] B. Pimentel, "Work Is Never Going Back to what it once Was", Business Insider," 2020, https://www.businessinsider.com/bill-mcdermottcoronavirus-%20digital-transformation-workplace-2020-3.

[25] H. K. Gardner and I. Matviak, "Coronavirus could force teams to work remotely," 2020, https://hbr.org/%202020/03/coronavirus-could-force-teams-to-work-remotely.

[26] P. Tiwari, J. K. Sadeghi, and C. Eseonu, "A sustainable lean production framework with a case implementation: practice-based view theory," *Journal of Cleaner Production*, vol. 277, no. 1, pp. 123078–123150, 2020.

[27] R. Henao, W. Sarache, and I. Gómez, "Lean manufacturing and sustainable performance: trends and future challenges," *Journal of Cleaner Production*, vol. 208, no. 1, pp. 99–116, 2019.

[28] L. Huston and N. Sakkab, "Connect and develop: inside procter & gamble's new model for innovation," *Harvard Business Review*, vol. 84, no. 3, pp. 58–66, 2006.

[29] R. K. Russell and D. D. Tippett, "Critical success factors for the fuzzy front end of innovation in the medical device industry," *Engineering Management Journal*, vol. 20, no. 3, pp. 36–43, 2008.

[30] J. Campos, D. Worseley, and B. Buxton, *Leveraging New Product Metrics to Gain Velocity*, Rapidinnovation, LLC, Seltice Way, Post Falls, USA, 2010.

[31] G. A. Moore, "Darwin and the demon: innovating within established enterprises," *Harvard Business Review*, vol. 82, no. 7-8, pp. 86–92, 2004.

[32] T. Supriyasilp, K. Pongput, and T. Boonyasirikul, "Hydropower development priority using MCDM method," *Energy Policy*, vol. 37, no. 5, pp. 1866–1875, 2009.

[33] Y. Celikbilek and F. Tuysuz, "An integrated grey based multi-criteria decision making approach for the evaluation of renewable energy sources," *Energy*, vol. 115, no. 1, pp. 1246–1258, 2016.

[34] L. Abdullah and L. Najib, "Sustainable energy planning decision using the intuitionistic fuzzy analytic hierarchy process: choosing energy technology in Malaysia," *International Journal of Sustainable Energy*, vol. 35, no. 4, pp. 360–377, 2016.

[35] F. Cucchiella, I. D'Adamo, M. Gastaldi, S. L. Koh, and P. Rosa, "A comparison of environmental and energetic performance of European countries: a sustainability index," *Renewable and Sustainable Energy Reviews*, vol. 78, no. 1, pp. 401–413, 2017.

[36] A. T. D. Perera, R. A. Attalage, K. K. C. K. Perera, and V. P. C. Dassanayake, "A hybrid tool to combine multi-objective optimization and multi-criterion decision making in designing standalone hybrid energy systems," *Applied Energy*, vol. 107, no. 1, pp. 412–425, 2013.

[37] E. O. Diemuodeke, S. Hamilton, and A. Addo, "Multi-criteria assessment of hybrid renewable energy systems for Nigeria's coastline communities," *Energy, Sustainability and Society*, vol. 6, no. 1, pp. 26–38, 2016.

[38] T. Balezentis and D. Streimikiene, "Multi-criteria ranking of energy generation scenarios with Monte Carlo simulation," *Applied Energy*, vol. 185, no. 1, pp. 862–871, 2017.

[39] M. Vafaeipour, S. Hashemkhani Zolfani, M. H. Morshed Varzandeh, A. Derakhti, and M. Keshavarz Eshkalag, "Assessment of regions priority for implementation of solar projects in Iran: new application of a hybrid multi-criteria decision making approach," *Energy Conversion and Management*, vol. 86, no. 1, pp. 653–663, 2014.

[40] T. Tsoutsos, M. Drandaki, N. Frantzeskaki, E. Iosifidis, and I. Kiosses, "Sustainable energy planning by using multi-criteria analysis application in the island of Crete," *Energy Policy*, vol. 37, no. 5, pp. 1587–1600, 2009.

[41] H. R. Quijano, B. S. Botero, and B. J. Dominguez, "Integrated simulation platform to promote and develop renewable sustainable energy plans, Colombian case study. Renew," *Sustain. Energy Rev*, vol. 16, no. 1, pp. 5176–5187, 2012.

[42] G. Dall'O', M. F. Norese, A. Galante, and C. Novello, "A multi-criteria methodology to support public administration decision making concerning sustainable energy action plans," *Energies*, vol. 6, no. 8, pp. 4308–4330, 2013.

[43] D. Streimikiene and T. Balezentis, "Multi-objective ranking of climate change mitigation policies and measures in Lithuania," *Renewable and Sustainable Energy Reviews*, vol. 18, no. 1, pp. 144–153, 2013.

[44] E. Triantaphyllou, *Multi-Criteria Decision Making Methods: A Comparitive Study*, Kluwer Academic Publishers, Dordrecht, Netherlands, 2000.

[45] V. Belton, "A comparison of the analytic hierarchy process and a simple multi attribute value function," *European Journal of Operational Research*, vol. 26, no. 1, pp. 7–21, 1986.

[46] E. H. Forman and S. I. Gass, "The analytic hierarchy process—an exposition," *Operations Research*, vol. 49, no. 4, pp. 469–486, 2001.

[47] P. J. H. Schoemaker and C. C. Waid, "An Experimental Comparison of different approaches to determining weights in additive utility models," *Management Science*, vol. 28, no. 2, pp. 182–196, 1982.

[48] M. Rogers, *Engineering Project Appraisal*, Blackwell Science, Inc, Oxford, UK, 2001.

[49] T. L. Saaty, "Decision making with the analytic hierarchy process," *International Journal of Services Sciences*, vol. 1, pp. 83–98, 2008.

[50] Y. Sato, "Comparison between multiple-choice and analytic hierarchy process: measuring human perception," *International Transactions in Operational Research*, vol. 11, no. 1, pp. 77–86, 2004.

[51] W. Ho, "Integrated analytic hierarchy process and its applications – a literature review," *European Journal of Operational Research*, vol. 186, no. 1, pp. 211–228, 2008.

[52] W. Ho, X. Xiaowei, and D. K. Prasanta, "Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. European Journal of Operational Research," vol. 202, no. 1, pp. 16–24, 2010.

[53] M. Abdel-Basset, A. Atef, and F. Smarandache, "A hybrid neutrosophic multiple criteria group decision making approach for project selection," *Cognitive Systems Research*, vol. 57, no. 1, pp. 216–227, 2019.

[54] Y. J. Wu and J.-C. Chen, "A structured method for smart city project selection," *International Journal of Information Management*, vol. 56, Article ID 101981, 2021.

[55] F. Zhou, Xu Wang, M. K. Lim, Y. He, and L. Li, "Sustainable recycling partner selection using fuzzy DEMATEL-AEW-FVIKOR: a case study in small-and-medium enterprises (SMEs)," *Journal of Cleaner Production*, vol. 196, no. 1, pp. 489–504, 2018.

[56] F. Zhou, Xu Wang, M. Goh, L. Zhou, and Y. He, "Supplier portfolio of key outsourcing parts selection using a two-stage decision making framework for Chinese domestic auto-

maker," *Computers & Industrial Engineering*, vol. 128, no. 1, pp. 559–575, 2019.
[57] R. Alyamani and S. Long, "The application of fuzzy analytic hierarchy process in sustainable project selection," *Sustainability*, vol. 12, no. 20, p. 8314, 2020.
[58] H. J. Mohammed, "The optimal project selection in portfolio management using fuzzy multi-criteria decision-making methodology," *Journal of Sustainable Finance & Investment*, pp. 1–17, 2021.
[59] T. L. Saaty, *The Analytic Hierarchy Process*, McGraw-Hill, New York, NY, USA, 1980.
[60] R. G. Cooper, S. J. Edgett, and E. J. Kleinschmidt, *Portfolio Management For New Products*, Perseus Books, New York, NY, USA, 1998.
[61] Gics, *Global Industry Classification Standard: Methodology*, Investopedia, New York, NY, USA, 2008.
[62] L. Seboni, "Improving the Existing Project Manager-To-Project Practice of a Specific Organization (Organization A) in Botswana," University of Leeds, Leeds, UK, PhD Theses, 2016.
[63] A. J. Mason, "OpenSolver – an open source add-in to solve linear and integer progammes in excel," in *Operations Research Proceedings 2011*Springer, Berlin, Germany, 2011.
[64] B. Meindl and M. Templ, "Analysis of commercial and free and open source solvers for the cell suppression problem," *Transactions on Data Privacy*, vol. 6, no. 2, pp. 147–159, 2013.
[65] D. N. P. Murthy, N. W. Page, and E. Y. Rodin, *Mathematical Modelling: A Tool for Problem Solving in Engineering, Physical, Biological and Social Sciences*, Pergamon, Bergama, Turkey, 1990.
[66] R. Y. Kim, "The impact of COVID-19 on consumers: preparing for digital sales," *IEEE Engineering Management Review*, vol. 48, no. 3, pp. 212–218, 2020.
[67] F. Lauren, "iPhone manufacturing in China is in limbo amid coronavirus outbreak," 2020, https://www.cnbc.com/2020/02/10/coronavirus-leaves-status-of-apple-manufacturing-in-china-uncertain.html.
[68] A. Ishizaka, D. Balkenborg, and T. Kaplan, "Influence of aggregation and preference scale on ranking a compromise alternative in AHP," *Multidisciplinary Workshop on Advances in Preference Handling*, Garda, Phoenix Park, Dublin, 2006.
[69] F. Lootsma, "Conflict resolution via pairwise comparison of concessions," *European Journal of Operational Research*, vol. 40, no. 1, pp. 109–116, 1989.
[70] T. Kainulainen, P. Leskinen, P. Korhonen, A. Haara, and T. Hujala, "A statistical approach to assessing interval scale preferences in discrete choice problems," *Journal of the Operational Research Society*, vol. 60, no. 2, pp. 252–258, 2009.
[71] R. J. Calantone, C. A. Benedetto, J. B. Schmidt, and J. B. Schmidt, "Using the analytic hierarchy process in new product screening," *Journal of Product Innovation Management*, vol. 16, no. 1, pp. 65–76, 1999.
[72] A. Ishizaka and A. Labib, "Analytic hierarchy process and expert choice: benefits and limitations," *ORInsight*, vol. 22, no. 4, pp. 201–220, 2009.
[73] J. S. Dyer, "Remarks on the analytic hierarchy process," *Management Science*, vol. 36, no. 3, pp. 249–258, 1990.
[74] R. F. d. F. Aires and L. Ferreira, "The rank reversal problem in multi-criteria decision making: a literature review," *Pesquisa Operacional*, vol. 38, no. 2, pp. 331–362, 2018.
[75] J. S. Dyer, "Maut – multiattribute utility theory," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, M. Ehrgott, Ed., Springer, New York, NY, USA, 2005.
[76] C. Marxt and P. Link, "Success factors for cooperative ventures in innovation and production systems," *International Journal of Production Economics*, vol. 77, no. 3, pp. 219–229, 2002.
[77] E. Dane and M. G. Pratt, "Exploring intuition and its role in managerial decision making," *Academy of Management Review*, vol. 32, no. 1, pp. 33–54, 2007.
[78] N. Khatri and H. A. Ng, "The role of intuition in strategic decision making," *Human Relations*, vol. 53, no. 1, pp. 57–86, 2000.
[79] C. R. Johnson, W. B. Beine, and T. J. Wang, "Right-left asymmetry in an eigenvector ranking procedure," *Journal of Mathematical Psychology*, vol. 19, no. 1, pp. 61–64, 1979.