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A Multitheoretical Perspective

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How Artificial Intelligence Drives Sustainable Frugal Innovation: A Multitheoretical Perspective

Kannan Govindan

Abstract—**Recent globalization and industrialization efforts have pushed many companies to seriously consider innovation efficiency and its effectiveness. Industries seek to integrate innovation thinking in the company, resulting in different innovation theories. However, these theories become mostly ineffective when disruptions such as pandemics, political instability, or other natural events occur. In response to such disruptions, frugal innovation has been adopted in recent years because it can maximize efficiency with fewer resources. While frugal thinking is effective from an economic perspective, not enough attention has been devoted to exploring this innovative thinking method from the perspective of other pillars of sustainability (environment and society). This article focuses on this gap to deepen the understanding of sustainable frugal innovation in a recent business environment under various theoretical perspectives (triple bottom line, diffusion of innovation, and critical success factor theories). Technology is a vehicle for innovation, so this article integrates the technological advantages of AI with sustainable frugal innovation as a driving force for its effective implementation; other existing studies are limited. Integrating AI with sustainable frugal innovation requires precise actions that can be the result of understanding AIs critical success factors from the perspectives of sustainable frugal thinking. Therefore, this article analyzes the critical success factors for AI through grey DEMATEL. A research framework has been proposed and validated with a Danish case study context. Among 24 overall common critical success factors, "understanding the concept of AI" and "level of AI investment" in sustainable frugal innovation are identified as the most influential success factors. In addition, influential connections among other overall common success factors are presented. These findings could motivate industries to explore different options for successfully integrating AI with their sustainable frugal thinking, which may increase their business competitiveness during disruptions in a more sustainable way.**

Index Terms—**Artificial Intelligence (AI), critical success factor (CSF) theory, diffusion of innovation (DOI) theory, grey DEMATEL, success factors, sustainable frugal innovation, triple bottom line (TBL) theory.**

I. Introduction

INNOVATION always stays at the forefront among global companies that care more about the future. Innovation drives market economies through sustainable growth. For example, the entrepreneurial firm Tesla became the largest company in the automotive sector because of its innovative EV technologies. Several literature works (e.g., Maas *et al.* [65] and Kumar and Li [57]) confirmed that there is a specific correlation between the firm's financial success and innovation. Global entrepreneurs are naturally fascinated by innovation, but a common myth to define innovation is that it is all about creating new products. According to OCED [73], innovation is defined as "the implementation of a new or significantly improved product (good or service) or process, a new marketing method or a new organizational method in business practice, workplace organization or external relations." Through this definition, it is clear that innovation is not limited only to products; real innovation extends to other areas of a company's activities (including business models, products, and marketing). Various initiatives have been integrated into practice to embrace the innovation culture among entrepreneurial firms, and the contribution of technology in recent years seems to be significant. Technologies also offer a viable opportunity to address several other social issues, including climate change, aging population, and urbanization [31]. Many global companies view technologies as an effective enabling innovation; for example, Accenture [78] published a report on how their business moves futuristically through innovation with the help of technologies.

However, conventional innovation thinking has its own limitations. The recent pandemic caused sectors around the globe to slow down. Partial or complete lock-in mandates occurred in many countries, and such mandates increased panic buying and resulted in imbalances between supply and demand. Regardless of the affected nation, many companies during this pandemic were forced to work with half their capacity of resources (including human labor). These restrictions seriously affect the economic situation of global companies, especially those of SMEs. Existing innovation strategies are not prepared for these pandemic influences where less resources are offered, which in turn are the global companies as prey for this disruption. Even large companies faced great pressure on conventional innovation thinking due to the rising cost of R&D, according to Bloom *et al.* [16]. Counting from the 1930s, every year, the research expenditure has been increased by 5%. This forced the researchers to spend additional costs for the same level of research done earlier, which makes the researchers end up with insufficient expenditures. To address these limitations of conventional innovation, few researchers [35], [84] suggested frugal innovation. In the past, frugal innovation was a strategy suitable only for low-income countries where there are severe resource constraints [44]. However, raising barriers to recent innovation thinking makes frugal innovation best suited to all levels of a nation's development [93]. Therefore, it is better to focus on frugal innovation, even with a concern for worst case

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scenarios, where companies can maximize the efficiency with fewer resources.

The word "frugal" is a well-known definition for being thrifty or economical. But when frugal modifies innovation, its acronym should be parsed as follows: functional, robust, user-friendly, growing, affordable, and local [94]. It has been argued that frugal innovation can lead to sustainable development. However, there are not enough studies that integrate sustainable perspectives for frugal innovation [3]. Meanwhile, with the introduction of sustainable development goals (SDGs), companies are highly motivated to engage in sustainable operations that encourage researchers to integrate sustainability into frugal innovations that tackle unforeseen disruptions without affecting sustainability quotas. These discussions answer the question: *What is sustainable frugal innovation, and why now*?

As with other innovations, this least discussed, yet strong sustainable frugal innovation can also run through technologies. According to Zhang [104], among technologies, artificial intelligence (AI) has an advantage over others in terms of frugal innovations. This argument is further strengthened with the evidence from the work in [97]; according to Wright, improving frugal innovation with AI could lead to a company's growth. These statements are central to provide the answer to the question: *What is the significance of integrating AI into sustainable frugal innovation*?

Although several studies [26], [79] insist on the combination of achieving frugal innovation with AI, in contrast, limited attention has been so far received. No study has addressed the concern of sustainable frugal innovation with AI. Without academic studies, it is difficult for entrepreneurs to enable sustainable frugal innovation through AI. Entrepreneurs will face problems with the integration of AI into sustainable innovation thinking. Therefore, it is necessary to understand the critical success factors (CSFs) for AI implementation in sustainable frugal innovation. With these concerns, the following argument can be made: *What are the common success factors/drivers for AI implementation in sustainable frugal innovation*? and *What are the influential CSFs/drivers among identified common CSFs/drivers*? The first two research questions have already been discussed earlier in the section. The remaining issues will be addressed later in this article. Some studies [4], [68] have already examined the CSFs with different concerns (managerial, operational, strategic, IT infrastructure, and organizational) for the implementation of (AI) projects. However, these studies are mainly limited to applications (e.g., healthcare) that are not suitable for newly introduced sustainable frugal innovation. According to Alhashmi *et al.* [4], it is necessary to analyze the relationship between a particular application for efficient identification of CSFs using AI. The novelty and uniqueness of this article further strengthen the scientific literature through the following significant contributions.

1) It provides groundbreaking knowledge to integrate AI with sustainable frugal innovation.
2) It strengthens the importance of sustainable frugal innovation and its effective implementation by identifying CSF.
3) It sheds light on recommendations for achieving the influential success factors of AI customization.

A framework has been proposed to address the research issue in which the primary and secondary data have been used to bring together the common success factors for AI in terms of sustainable frugal innovation. The collected datasets were further analyzed using a laboratory method (DEMATEL) along with the grey theory.

Several facets of this research have been gained through the review of existing literature. Specifically, several studies focused on the relationship between sustainability and frugal innovation. Subsequently, more papers examine the impact of AI on sustainability and SDGs. But, in contrast, there is not enough evidence for the integration of AI in the application of frugal innovation. In addition, CSFs/drivers of AI adaptation have been mainly focused on the health sector. There is not a single study that combines sustainability and frugal innovation with CSFs of AI adoption. Hence, this article attempts to address this literature gap by analyzing the CSFs of AI adoption in sustainable frugal innovation based on the support of theoretical perspectives including triple bottom line (TBL) theory, diffusion of innovation (DOI) theory, and CSF theory.

Some of the research highlights from this article are listed in the following.

1) Identification of common CSFs in AI adaptation in sustainable frugal innovation from primary and secondary data sources (literature review, and industrial and field experts).
2) Proposed a framework to analyze the collected common CSFs with the assistance of the grey DEMATEL tool.
3) The proposed framework is validated with the application of a Danish case study context.
4) The influential CSFs of AI adaption in sustainable frugal innovation have been identified and validated by both primary (feedback of field and industrial experts) and secondary sources (existing literature).

The rest of this article is organized as follows. Section II offers a review of existing studies with three key focus areas: 1) sustainable frugal innovation, 2) entrepreneurship, and 3) AI. The problem has been described along with the proposed research framework in Section III. Section IV discusses the solution methodology, grey DEMATEL, along with its steps for implementation. Section V validates the proposed research framework by application through various phases. Section VI presents results and their corresponding discussions. Finally, Section VII concludes this article, which includes the key findings, implications and recommendations, limitations, and scope for future directions.

II. Literature Review

This section intends to explore the different phenomena involved in the study through academic perspectives. Three different subsections have been introduced: 1) frugal innovation and sustainability; 2) frugal innovation and entrepreneurship; and 3) AI–CSFs, (frugal) innovation, sustainability, and review of theories.

A. Frugal Innovation and Sustainability

Several studies [25], [55], [91], [92] discuss various aspects of frugal innovation, and the number of publications has especially increased after the pandemic. However, comparatively fewer studies focus on the sustainable advantages of frugal innovation. Few studies attempt to establish the concepts of frugal innovation with sustainability. Albert [3] explored the connection between sustainability and frugal innovation and proved that frugal innovation is socially and economically sustainable. Hassani *et al.* [43] reviewed frugal innovation and its impacts of sustainability in supply chain optimization; they further proposed a numerical model to integrate frugal innovation and sustainable development. Rosca *et al.* [83] investigated business models with the concern of frugal and reverse innovation through 59 frugal products and services. Hossain *et al.* [45] studied three different frugal innovation cases concerned with their sustainable contributions. This article argued that frugal innovation can unlock the potential to provide affordable markets within limited resources including funding. Rosca *et al.* [82] did a literature review in which their study addressed a research question, "does frugal innovation enable sustainable development?," in relation to several actors of private sectors. Few studies explain frugal innovation with sustainability applications. For instance, Shibin *et al.* [86] studied the Indian context supply chain challenges including institutional barriers and resources constraints; frugal innovation was discussed as a solution for addressing these challenges and to maintain sustainability in the supply chain.

Few studies focused on analyzing the interrelationship between frugal innovation and sustainability and sustainable performances. Iqbal *et al.* [48] correlated frugal innovation leadership with sustainable performance through four propositions; furthermore, this article attempted to embrace the managers and policymakers to understand the hidden sustainable advantages of frugal innovation. Some studies connected the impact of frugal innovation with SDGs. For instance, Arnold [8] analyzed 50 different frugal innovations with their contributions to SDGs and further confirmed that frugal innovation was a major driver of SDGs implementation. Dressler and Bucher [30] proposed and applied a framework on an African case context to express the links between SDGs and frugal innovation. Some studies focused on one or two dimensions of sustainability with frugal innovation perspectives. Bas [12] argued frugal innovation as an environmental innovation and further strengthened the argument with a framework accounting model in which the success factors and barriers for frugal innovation were studied. Dost *et al.* [29] analyzed the interrelationship between the effects of internal and external sources of frugal innovation in a firm's environmental turbulence. Khan [53] connected the links between frugal innovation and social sustainability through a proposed framework in which the social sustainability themes were explored through frugal innovation.

Few studies work on the resource-based sustainability in frugal innovation; for instance, Molina-Maturano *et al.* [69] studied frugal innovation with the concern of water resources to improve the status of Mexican sustainable development. Hyvarinen *et al.* [46] explored the Tanzanian water crisis through frugal innovation and further interrelates it with sustainability. Levanen *et al.* [59] considered water and energy innovations through the perspectives of frugal thinking; in addition, this article identified several challenges of frugal innovation with the concern of the spare use of water and energy.

These examples demonstrate that there is a positive correlation between sustainability and frugal innovation, so improving sustainable frugal innovation thinking leads to achieving SDGs more promptly.

B. Frugal Innovation and Entrepreneurship

From the academic perspective, several studies [15], [67], [76], argue there is a correlation between the innovation and the success of entrepreneurship. To be specific, the publication density of innovation-based entrepreneurship is high. Some 3341 documents can be identified with the search string of innovation and entrepreneurship; however, this search is limited by various concerns (for instance, subject area as a business, source type as a journal, and so on). Furthermore, this number can be easily exceeded. Contrary to the previous numbers, very few studies demonstrate the concern of frugal innovation and entrepreneurship, and this gap clearly shows the lack of research and inherent opportunities in this field. Some studies consider frugal innovation along with other innovation theories with entrepreneurship. For instance, Ghorbel *et al.* [39] attempted to link different innovation theories with effectual logic for entrepreneurial research, to include frugal, disruptive, design thinking, and lean start-up innovations. Farooq [33] developed a conceptual framework model with frugal innovation to contribute toward the entrepreneurship literature strategically.

Only very few studies targeted the core of entrepreneurship with the sole focus of frugal innovation. For instance, Igwe *et al.* [47] studied the correlation between the entrepreneurship ecosystem along with the development of frugal innovation and informal entrepreneurship. This article considers 20 different Nigerian business cases to understand the barriers to entrepreneurship and to overcome those barriers through the determinants of frugal innovation. Pesa [75] focused on entrepreneurship and labor relations through the development potential of frugal innovation in Zambia. This article attempted to foster entrepreneurship in the field of mobile money agents, in which 52 agents were surveyed. Jain [50] studied and incorporated the benefits of adapting frugal innovation with the success of entrepreneurship. Furthermore, this article highlights various intangible benefits of integrating a frugal approach in a firm's innovation to facilitate entrepreneurship through optimized practice and policy discourses.

C. AI–CSFs, (Frugal) Innovation, and Sustainability

This subsection has been designed with three key elements corresponding to the concerned research: namely, CSFs, innovation, and sustainability. Studies published on AI generally detail its CSFs and their application on (frugal) innovation and sustainability. Regarding CSFs, there are few studies to be seen, so this review also includes the drivers of AI. Mir *et al.* [68] discussed the CSFs of AI adaption through the application of intelligent autonomous systems. Total interpretative structure modeling has been used to analyze the considered CSFs, in which policies are identified as the major CSFs. Leitao *et al.* [58] explored the AI drivers through industrial agent applications, in which more generic drivers of AI adaption were mentioned, which includes robustness, scalability, reconfigurability, and productivity.

Some studies include AI under the umbrella term Industry 4.0 technologies in order to investigate the CSFs. Bag and Pretorius [10] completed a literature review on drivers, challenges, and opportunities of big data and AI adaption, and this review integrated various concepts including sustainable manufacturing, circular economy, and Industry 4.0 technologies. Some studies merely focused CSFs on different applications (health sector, agriculture, and so on) of AI. For instance, Rodzalan *et al.* [81] explored the drivers of AI in the agricultural sector using a tool, STEEPV. This article concluded with two key drivers of AI in an agricultural context, namely, the replacement of employees and productivity enhancements. Cubric [23] studied the drivers, barriers, and other social considerations of AI adaption in a business context, in which most of the key drivers of AI adoption are identified from economic perspectives. Compared to other sectors, health care sectors have comparatively a greater number of studies with the concern of AI adaption; see, for instance, Alhashmi *et al.* [5] and Yoon and Lee [102]. Renz and Hilbig [80] studied the application of AI in the education sector by analyzing the drivers, barriers, and existing business models. Belanche *et al.* [13] identified the key drivers of robo-advisors in fintech companies, which is a successful application of AI in recent years; this article sought to strengthen the understanding of customers' perceptions regarding the integration of AI technologies in fintech.

There are several studies [70] that concern innovation and AI. Haefner *et al.* [42] offered a literature review on these existing studies, which simplified the connection between AI and innovation management. However, in terms of AI with frugal innovation, no solid studies are found in the review except for some grey literatures. On the other hand, numerous studies can be seen with the connection of AI with sustainability and sustainable development. These results include various literature review papers in different applications, including food [19], building [66], and business models [28]. Very few works combined innovation, sustainability, and AI, but, for example, Ortega-Fernández *et al.* [74] and Alami *et al.* [2] explored the impact of AI in innovation and sustainability with the applications of smart cities and health care, respectively.

D. Review of Theories

As a part of the literature review, this article reviews three different theories that are closely related to the considered study: 1) TBL theory, 2) DOI theory, and 3) CSF theory. Each theory relates to the considered phenomenon of the study (sustainability, frugal innovation, and success factors).

1) TBL Theory: Unsuccessful innovation activities will inevitably cause a major financial loss in any concerned institution. Hence, it is necessary to balance the innovation actions with financial aspects; recent years produce evidence of increasing pressures to include other elements (environment and society) above and beyond finance perspectives. This motivates this article to consider sustainable development as one phenomenon and to necessarily understand the theory behind a review of sustainability theory. TBL theory has been used since 1997 for the development of sustainability-related studies. It was first introduced by Elkington to assist firms in transforming their focus solely away from finance to other impact factors associated with the firm's activities. This theory revolves around three "P"s: 1) people, 2) planet, and 3) prosperity.

Each of the three "P"s' emphasizes one element of sustainability (society, environment, and economy), but in recent years each "P" has been motivated through various strategies: for instance, people through corporate social responsibility, the planet through climate change, and prosperity through SDGs. Several studies [63], [103] seek to identify the relationship between TBL theory and other theories (such as sustainable supply chain theory, green supply chain theory, and so on). Owing to the advantages of considering TBL theory in the study, several researchers started to integrate the TBL theory in various fields of applications. Among those fields, supply chains [61] received more attention. Although several studies consider the TBL theory, a gap still exists with the integration of TBL theory with innovation. Very few studies [24] sought to analyze the interrelationships of the TBL approach and innovation, and literature resources are majorly short on frugal innovation with the TBL theory.

2) DOI Theory: One major phenomenon considered in this article is innovation. With this perspective, it is viable to understand the theory behind the innovation process to better integrate with other elements considered in this article. While several innovation theories exist within the literature, this study selects the DOI theory due to its reliability. DOI theory is probably one of the oldest theories, first introduced by E.M. Rogers in 1962 in his book, "*Diffusion of Innovation.*" First, this theory was introduced to focus on social science theories, but because of its benefits, it has been extensively applied in various applications [108], [109]. Mostly, this theory is used to communicate the innovation ideas within certain channels. Four elements have been used to construct this theory: 1) innovation (idea), 2) channel (communication channel), 3) social system (network group), and 4) time. This theory assists practitioners to understand the effects of adopting innovative ideas among the social members involved. The effect on social members can be identified in five categories of DOI theory, including innovators (bringing new ideas), early adopters (willing to adopt new ideas), early majority (innovations are rapidly chosen based on evidence), late majority (innovations are eventually adopted on a large-scale generated from other's outcomes), and, finally, laggards (conservatives, do not want to change). This article integrates the DOI theory through frugal innovation, where only two studies currently exist [87], [105].

3) CSF Theory: Since the introduction of CSF theory by John Rockart in 1979, literature provides several successful examples of evidence. While this theory was first introduced in the field of information systems, owing to its efficiency, it has been applied to several other fields of applications. Rockart defined the CSFs as "The limited number of areas in which satisfactory results will ensure successful competitive performance for the individual, department or organization. Critical success factors are the few key areas where 'things must go right' for the business to flourish and for the manager's goals to be attained" [110]. With this definition, practitioners often confused the "success factors" with goals, but goals are more outcome-oriented, whereas success factors are more comprehensive and achieved through strong leadership's mission and vision. With the application of success factors in different fields, several studies define success factors in their own means. A popularly accepted laymen definition was given by Boynton and Zmud [111] as, "those few things that must go well to ensure success," and, according to Kannan [51] and Dora *et al.* [112], this definition is universally flexible and may be applied to any field of applications.

Success factors have a big influence on a firm's goals and objectives. Success factors may be the result of neglecting the ambiguity involved in the organization through explicit communication on concerned phenomena [113]. However, in recent years, the CSFs have been transformed as a concept that covers all areas of business management in addition to explicit communication as discussed by Caralli *et al.* [113]. Owing to this influence, studies started to investigate the success factors without regard to the level and status of the organization [51]. These studies used the CSFs to identify the risks and opportunities associated with the goals and objectives concerning both the internal and external environments of the firm. These success factors are quantifiable, so it is easy for an organization to monitor its progress and then improve the effectiveness of the organization. Most of the CSF theory-based studies used case study methodology and the Delphi methodology for analysis. In addition, most of the CSF theory constraints build upon five pillars: 1) competition, 2) external environmental factors, 3) priorities, 4) strategy, and 5) time-sensitive circumstances [110], [113]. Many studies repeatedly claimed that each industrial sector (including manufacturing and service) develops its own set of success factors of reaching the strategic goals and objectives. This article examines three key phenomena: 1) AI, 2) frugal innovation, and 3) sustainability. Among these, frugal innovation [114] has registered a smaller number of CSF studies where sustainability includes more research papers on CSF. To the best of our knowledge, no previous study integrates the CSF theory in sustainable frugal innovation, so this article could be pioneering work for further explorations.

III. Case Description and Research Framework

While the recent pandemic has affected all countries around the globe, EU nations have been affected more dramatically than South Asian countries. Several industries were shut down, and some industries were forced to operate under partial resources. Governments tried to deliver stimulus packages to the hardest-hit industrial sectors. As discussed in the previous section, frugal innovation has gained momentum during and after this pandemic, especially in developed countries, so this article considers such a developed context, Denmark, as a case study. According to Yin [101], case study methods can help researchers understand the profound complexity of the problem, and they seek to result in an optimized choice of solutions. This reputable company has a long history in the design, manufacture, and installation of expansion joints. The products of this case company have been served all over the world, including fabric, elastomer, and metal expansion joints. These expansion joints are used in various applications, including chemical plants, power plants, gas turbines, oil rigs, cement factories, steel mills, and offshore. In addition, the company caters their services based on their customers, allowing the customer to design their own products. Although the case company has a strong presence in the business market, the recent pandemic aggressively cut their profits and productivity.

The company's past experience with innovation could not offset the pandemic's impact. While they are slowly recovering from the impact, the case company needs to improve their responsiveness to such influences in the future to achieve their full potential with fewer resources. Therefore, they are interested in focusing on frugal innovation in their company's activities. In addition, this case is more focused on several sustainable strategies, which include reducing resource consumption and waste production, reducing transportation costs, tracking the supplier's green activities, waste sorting, and ensuring compliance with government regulations. Therefore, they want to make frugal innovation sustainable. This is the main reason why the case company accepts our proposal for a research group to investigate sustainable frugal innovation. As the case company is in an initial phase, they will explore different options for better implementation of sustainable frugal innovation. AI is already built-in to their portfolio, so they are capable to observe the integrated AI effect on sustainable frugal innovation. To understand the effective alignment of AI in their firm's sustainable frugal innovation thinking, the case company needs a pilot study to analyze the success factors, and that objective coincides with the rationale of this article. To achieve the considered objectives, a research framework has been proposed as shown in Fig. 1. The research framework has started with data collection for which both primary and secondary sources have been used; data include advanced review and the opinions of case and field experts. Based on these sources, the common CSFs for AI adaptation in sustainable frugal innovation have been identified. In addition, the collected CSFs have been introduced to the decision makers in the case, and based on their responses, CSFs were evaluated through grey DEMATEL. Based on the diagraph, the influence of the CSF and their interrelationships are identified. To remove bias and validate the results, a feedback program has been implemented, where results are utilized with the previously used primary and secondary sources.

IV. Solution Methodology

AI is in its infancy with concerns about frugal innovation and, consequently, there are many opportunities for complexity within the problem. The problem must be structured before the solution is made. In addition, understanding the influential CSFs involves several factors in the decision-making process. In terms of fact, this study used multicriteria decision-making (MCDM) methods to analyze the CSFs of AI adaptation in sustainable frugal innovation. According to Li *et al.* [60], MCDM methods are best suited to understand interactions and conflicts between the factors considered; they argue that this benefit leads to MCDM being used in more diverse applications. With the MCDM family, there are several tools. Each of the tools is known for its unique properties, but this study considers DEMATEL with the grey theory. The reasons for considering this method are discussed in the following sections.

A. Grey Approach

MCDM methods (regardless of tool) contain judgments from the decision makers, and sometimes these judgments demonstrate some bias and ambiguity. In addition, because the integration of AI into sustainable frugal innovation is a new, growing area, incomplete data might be seen, which may further increase the risk of limiting the reliability of the end results. To address these limitations of MCDM tools, researchers began to integrate grey theory. This theory has been used to process informal data into formal data, and it further helps the decision makers to complete the results even with smaller/partial data [38]. The grey theory was first introduced by Deng [27] from a grey set, and it was applied successfully [20], [89], [99] in several areas. The three-step procedure involved in the grey theory is given below in the equations where the grey numbers are converted to crisp numbers for easy calculation using a modified CFCS method [106].

B. DEMATEL Method

Decision-making trial and evaluation laboratory (DEMATEL) is a successful MCDM tool in terms of analyzing the interrelationship and influence among considered criteria. This was first proposed by Gabus and Fontela, in 1972 at Battelle Memorial Institute, Geneva Research Center [41]. The major advantage of this tool is that it allows decision makers to imagine the problem with a better structure that assists them to understand the causal relationships among considered complex criteria. The

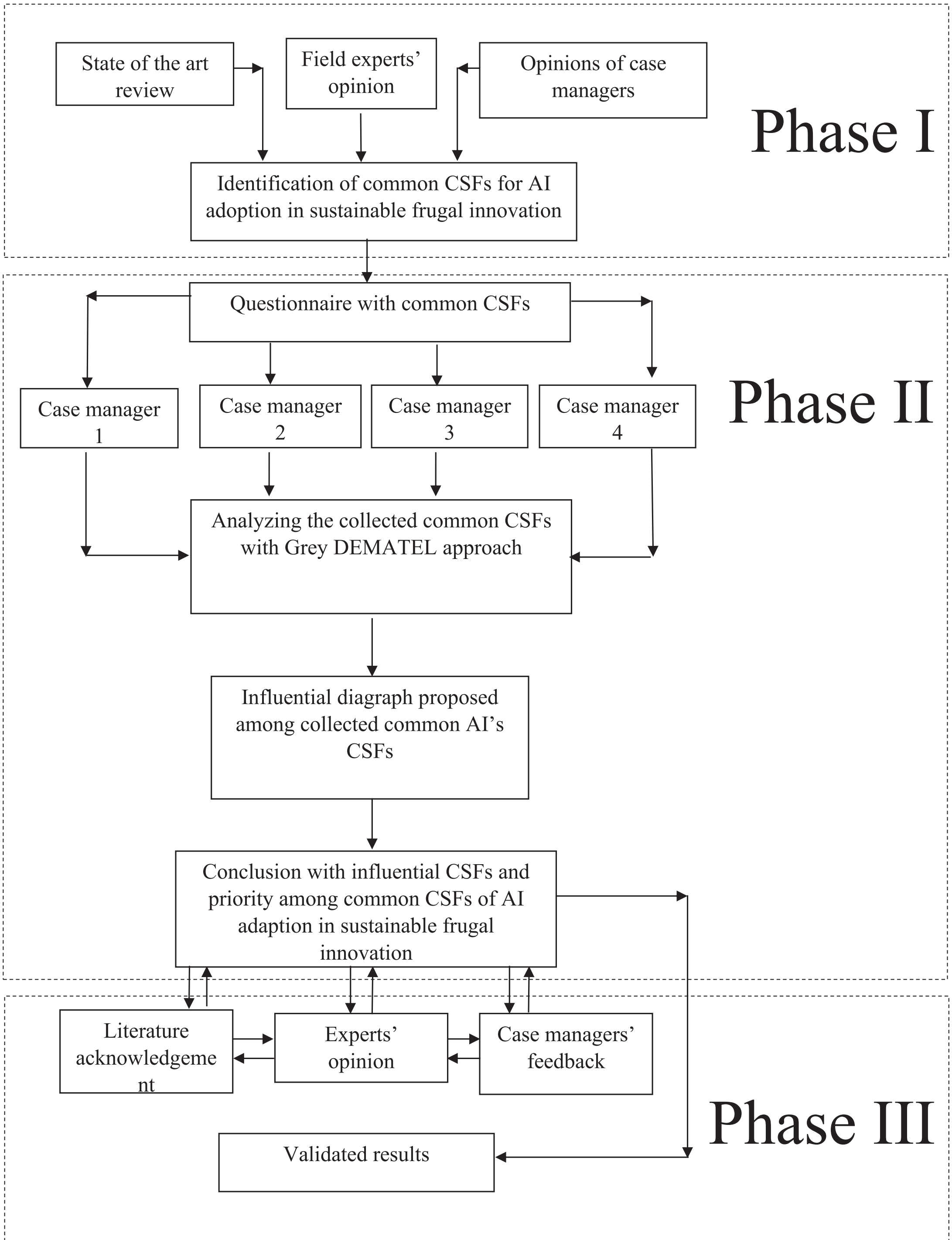

Fig. 1. Proposed research framework.

DEMATEL method primarily uses a diagraph to explain the relationship among the criteria; the criteria will be classified into two groups, namely, 1) causal and 2) effect groups. Based on the criteria's position in the group decides whether it is an influential criterion or an influence. The criteria that hold a position in the cause group are the influential criteria that usually influence other existing criteria, whereas the criteria that hold a position in the effect group are usually influenced by the influential criteria. Due to the easily understandable pictorial representation, decision makers are confident with their findings, so this advantage leads DEMATEL to serve in several applications [34], [52], [100]. Although DEMATEL is best suited for analyzing criteria, it still has its own limitations especially in instances of less/partial data. The probability for bias in DEMATEL exists due to this lack of information, but generally, this limitation has been addressed through either fuzzy theory or grey theory by researchers. However, comparatively, a grey theory has more advantages than the fuzzy theory because the grey theory considers fuzziness, which is limited in fuzzy theory [98]. Owing to these advantages, several successful applications are evident with grey DEMATEL [40], [62]. Due to the solid features of grey DEMATEL, this study selected this methodology for analyzing the CSFs for AI adoption in sustainable frugal innovation.

C. Steps Involved in Grey DEMATEL

Step 1: Initial crisp relation matrix "F"

The first step is to set up an initial crisp relation matrix based on decision makers' rating over given criteria. However, the decision makers' response has been received in the form of grey numbers and this has been transformed through grey theory as shown in (1)–(3). The form of the initial crisp relation matrix is shown in (4):

(1) Normalization

$$\underline{\otimes}\overline{x}_{ij}^{k} = (\underline{\otimes}x_{ij}^{k} - \min \underline{\otimes}x_{ij}^{k})/\Delta_{\min}^{\max}$$
$$\overline{\otimes}\overline{x}_{ij}^{k} = (\overline{\otimes}x_{ij}^{k} - \min \underline{\otimes}x_{ij}^{k})/\Delta_{\min}^{\max} \text{ where } \Delta_{\min}^{\max} = \max \overline{\otimes}x_{ij}^{k} - \min \underline{\otimes}x_{ij}^{k} \quad (1)$$

(2) Determination of a total normalized crisp value

$$Y_{ij}^{k} = \frac{\underline{\otimes}\,\overline{x}_{ij}^{k}(1 - \underline{\otimes}\,\overline{x}_{ij}^{k}) + \overline{\otimes}\,\overline{x}_{ij}^{k} \times \overline{\otimes}\,\overline{x}_{ij}^{k}}{1 - \underline{\otimes}\,\overline{x}_{ij}^{k} + \overline{\otimes}\,\overline{x}_{ij}^{k}} \quad (2)$$

(3) Computation of final crisp values

$$z_{ij}^{k} = \min \underline{\otimes}x_{ij}^{k} + Y_{ij}^{k}\Delta_{\min}^{\max} \quad (3)$$

$\tilde{\boldsymbol{A}}$

$$\begin{bmatrix} 0 & \text{a12} & \text{a13} & \cdots & \text{a1(n}-1) & \text{a1n} \\ \text{a21} & 0 & \text{a23} & \cdots & \text{a2(n}-1) & \text{a2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \text{a(n}-1)1 & \text{a(n}-1)2 & \text{a(n}-2)3 & \cdots & 0 & \text{a(n}-1)\text{n} \\ \text{an1} & \text{an2} & \text{an3} & \cdots & \text{an(n}-1) & 0 \end{bmatrix}. \quad (4)$$

Step 2: Set up normalized direct-relation matrix "S"

The normalized direct relation matrix is obtained through (5) and (6). All elements in this matrix lie between 1 and 0

$$K = \frac{1}{\max}\ _{1\leq i\leq n} \sum_{j=1}^{n} a_{ij} \quad (5)$$

$$X = K \times F. \quad (6)$$

Step 3: Set up total relation matrix "M"

In this step we need to set up the total relation matrix *M*. The normalized matrix is processed by the formula in (7) where **I** denotes the identity matrix:

$$\boldsymbol{M} = \boldsymbol{X}\,(\boldsymbol{I} - \boldsymbol{X}) - 1. \quad (7)$$

Step 4: Obtain influential diagraph through the sum of rows and the sum of columns

D and R denote the sum of rows and the sum of columns. This should be calculated through (8) and (9):

$$\text{D} = \left[\sum_{j=1}^{n} mij\right] n \times 1 \quad (8)$$

$$\text{R} = \left[\sum_{i=1}^{n} mij\right] 1 \times n \quad (9)$$

$M = m_{ij}$, $i, j = 1, 2, \ldots, n$.

The causal and effect graph is obtained in this step by means of the dataset that consists of (**D + R, D – R**), where the horizontal axis (**D + R**) is made by adding **D** to **R**, and the vertical axis (**D – R**) is made by subtracting **R** from **D**.

V. Application of Proposed Framework

The proposed framework has been applied in the case industry through three phases, namely identification of common drivers/CSFs for AI implementation in sustainable frugal innovation, analysis of the impact among commonly collected CSFs/drivers through grey DEMATEL, and results and validation. All phases and their respective procedures have been detailed before starting the process for the decision makers. In this case, four caseworkers have been used as decision makers involved in different areas of the company's activities. As mentioned earlier, sustainable frugal innovation is a thinking that can be integrated into all the activities of the company. Therefore, these decision makers are considered in various operations of the case company, including R&D, store flooring (production), quality, and marketing. A detailed illustration of the proposed model is discussed below.

A. Phase I: Identification of Common Drivers/CSFs for AI Adaption in Sustainable Frugal Innovation

The first phase involves the collection of common CSFs of AI adaption in sustainable frugal innovation. The data sources were primary and secondary, in which the primary sources include experts' and case managers' opinions. The secondary sources consider the publications listed in the consulted databases, including SCOPUS and Web of Science. The collection of data starts from the secondary sources; search strings include "frugal innovation," "sustainable frugal innovation," "drivers of AI," "CSFs of AI," and so on. With the help of secondary sources, nearly 34 CSFs were collected. To ensure the gap between the practitioners' perspective and academic literature, primary sources have been used to validate this secondary data. For this validation, field experts and case managers were invited for a two-day workshop, in which the collected secondary data were presented. The collected CSFs were circulated with the participants, and at the end of two roundtable discussions, several modifications were made to the collected CSFs. First, the number of CSFs was reduced to 24 to avoid repetition, and the CSFs were categorized into sustainable frugal dimensions, which could further assist the industries to improve their desired sustainability pillars.

B. Phase II: Analyzing the Influence Among Common Collected CSFs Through Grey DEMATEL

In this phase, the collected and finalized CSFs have been analyzed through grey DEMATEL based on the replies of case decision makers (managers). For simplicity, all the managers have been assigned as equal weights; hence, there is no chance of undulation in end results.

TABLE I
COLLECTION OF COMMON CSFs FOR AI ADAPTION IN SUSTAINABLE FRUGAL INNOVATION

Dimensions of sustainable frugal innovation	CSF/drivers of AI	Notation	References
Economical frugal innovation	Promotion, incentives, and policy support from government	CSF1	[3], [14], [44], [43], [56], [82], [83], [92]
	Level of AI investment	CSF2	
Environmental frugal innovation	Green production support (9R)	CSF3	[3], [12], [29], [43], [44], [49], [82], [83]
	Reduced cycle/response time	CSF4	
	Multifunctionalities/upcycling	CSF5	
	Environmental performance measurement (value chain)	CSF6	
Social frugal innovation	Health and Safety	CSF7	[9], [43], [44], [46], [53], [59], [69], [82], [83], [84], [85], [94]
	Privacy management	CSF8	
	Transparency	CSF9	
	Resilience alert	CSF10	
Entrepreneurial (Operational) frugal innovation	Performance evaluation	CSF11	[8], [25], [35], [44], [48], [55], [91]
	Training of employees	CSF12	
	Centralized decision making	CSF13	
	Top management support	CSF14	
	Communication	CSF15	
Supply chain frugal innovation	Identification of AI partners	CSF16	[44], [79], [86], [93]
	Vendor support and cooperation on SFI	CSF17	
	Supply team facilitation	CSF18	
Technological frugal innovation	Understanding the concept of AI	CSF19	[4], [5], [22], [23], [26], [31], [54], [68], [70], [80], [104]
	Value chain technology supporting facilities	CSF20	
	Data quality and protection	CSF21	
	Integrated data warehouses	CSF22	
	Technology readiness	CSF23	
	Analytics capabilities	CSF24	

The step-by-step analysis of drivers with grey DEMATEL is given as follows.

Step 1: Develop a crisp direct-relation matrix.

This first step involves three substeps as follows.

1) A grey pairwise comparison has been made among collected common CSFs. First, decision makers can express their response in the linguistic scale as shown in Table II, which is further converted into grey values. The greyscale ranges from 0 to 4, in which 0 = no influence, 1 = Very low influence, 2 = Low influence, 3 = High influence, and 4 = Very high influence.
2) A grey pairwise direct relation matrix X has been developed as shown in Table III, in which the evaluators introduce the grey pairwise influence relationships ($\otimes_{i\times j}^{k}$) between the CSFs in 24×24 matrix. All four decision makers' responses have been compiled as one direct relation matrix.
3) With the assistance of the modified APR process, the grey direct-relation matrix is converted into

TABLE II
LINGUISTIC SCALES FOR THE IMPORTANCE WEIGHT OF EVALUATORS

Linguistic variable	Grey values
No influence	[0,0]
Very low	[0,0.25]
Low	[0.25,0.5]
High	[0.5,0.75]
Very high	[0.75,1.0]

TABLE III
GREY PAIRWISE COMPARISON

	CSF 1		CSF 2		CSF 3		CSF 4		CSF 5		CSF 6		CSF 7		CSF 8		CSF 9		CSF 10		CSF 11		CSF 12		CSF 13		CSF 14		CSF 15		CSF 16		CSF 17		CSF 18		CSF 19		CSF 20		CSF 21		CSF 22		CSF 23		CSF 24	
CSF1	0	0	0	0	0	0.25	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0	0	0	0.25	0	0	0.5	0.75	0	0.25	0	0.25	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25
CSF2	0.75	1	0	0	0.5	0.75	0.75	1	0.25	0.5	0.75	1	0.5	0.75	0.5	0.75	0.5	0.75	0.75	1	0.75	1	0.25	0.5	0.75	1	0.25	0.5	0.75	1	0.25	0.5	0.75	1	0.5	0.75	0	0.25	0.75	1	0.5	0.75	0.5	0.75	0.5	0.75	0.5	0.75
CSF3	0.75	1	0	0	0	0	0.5	0.75	0	0	0.5	0.75	0.25	0.5	0.25	0.5	0.5	0.75	0.75	1	0.75	1	0	0	0.75	1	0	0	0.75	1	0.5	0.75	0.75	1	0.5	0.75	0	0	0.75	1	0.5	0.75	0.25	0.5	0	0.25	0	0.25
CSF4	0.5	0.75	0	0	0	0.25	0	0	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0.5	0.75	0	0	0.5	0.75	0	0	0.5	0.75	0	0.25	0.5	0.75	0	0.25	0	0	0.5	0.75	0.5	0.75	0	0.25	0	0.25	0	0.25
CSF5	0.75	1	0	0.25	0.5	0.75	0.75	1	0	0	0.75	1	0.5	0.75	0.5	0.75	0.5	0.75	0.75	1	0.75	1	0.25	0.5	0.75	1	0.25	0.5	0.75	1	0.25	0.5	0.75	1	0.5	0.75	0	0.25	0.75	1	0.5	0.75	0.5	0.75	0.5	0.75	0.5	0.75
CSF6	0.5	0.75	0	0	0	0.25	0.5	0.75	0	0	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0.5	0.75	0	0	0.5	0.75	0	0	0.5	0.75	0	0.25	0.5	0.75	0	0.25	0	0	0.5	0.75	0.5	0.75	0	0.25	0	0.25	0	0.25
CSF7	0.75	1	0	0	0	0.25	0.5	0.75	0	0	0.5	0.75	0	0	0	0.25	0	0.25	0.5	0.75	0.75	1	0	0	0.75	1	0	0	0.75	1	0	0.25	0.75	1	0.25	0.5	0	0	0.5	0.75	0.5	0.75	0	0.25	0	0.25	0	0.25
CSF8	0.75	1	0	0	0	0.25	0.5	0.75	0	0	0.5	0.75	0.25	0.5	0	0	0.5	0.75	0.75	1	0.75	1	0	0	0.75	1	0	0	0.75	1	0.5	0.75	0.75	1	0.5	0.75	0	0	0.75	1	0.5	0.75	0	0.25	0	0.25	0	0.25
CSF9	0.75	1	0	0	0	0.25	0.5	0.75	0	0	0.5	0.75	0.25	0.5	0	0.25	0	0	0.5	0.75	0.75	1	0	0	0.75	1	0	0	0.75	1	0.25	0.5	0.75	1	0.25	0.5	0	0	0.5	0.75	0.5	0.75	0	0.25	0	0.25	0	0.25
CSF10	0.5	0.75	0	0	0	0.25	0.5	0.75	0	0	0.5	0.75	0	0.25	0	0.25	0	0.25	0	0	0.5	0.75	0	0	0.5	0.75	0	0	0.5	0.75	0	0.25	0.5	0.75	0	0.25	0	0	0.5	0.75	0.5	0.75	0	0.25	0	0.25	0	0.25
CSF11	0.5	0.75	0	0	0	0.25	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0	0	0	0	0	0.25	0	0	0.5	0.75	0	0.25	0.5	0.75	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25
CSF12	0.75	1	0	0.25	0.5	0.75	0.75	1	0	0.25	0.75	1	0.5	0.75	0.5	0.75	0.5	0.75	0.75	1	0.75	1	0	0	0.75	1	0	0.25	0.75	1	0.25	0.5	0.75	1	0.5	0.75	0	0.25	0.75	1	0.5	0.75	0.5	0.75	0.5	0.75	0.5	0.75
CSF13	0.5	0.75	0	0	0	0.25	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0.5	0.75	0	0	0	0	0	0	0.5	0.75	0	0.25	0.5	0.75	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25
CSF14	0.75	1	0	0.25	0.5	0.75	0.75	1	0	0.25	0.75	1	0.5	0.75	0.5	0.75	0.5	0.75	0.75	1	0.75	1	0.25	0.5	0.75	1	0	0	0.75	1	0.25	0.5	0.75	1	0.5	0.75	0	0.25	0.75	1	0.5	0.75	0.5	0.75	0.5	0.75	0.5	0.75
CSF15	0	0.25	0	0	0	0.25	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0	0	0	0.25	0	0	0	0	0	0.25	0	0.25	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25
CSF16	0.75	1	0	0	0	0.25	0.5	0.75	0	0	0.5	0.75	0.25	0.5	0	0.25	0	0.25	0.5	0.75	0.75	1	0	0	0.75	1	0	0	0.75	1	0	0	0.75	1	0.25	0.5	0	0	0.5	0.75	0.5	0.75	0	0.25	0	0.25	0	0.25
CSF17	0.5	0.75	0	0	0	0.25	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0	0	0	0.25	0	0	0.5	0.75	0	0.25	0	0	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25
CSF18	0.75	1	0	0	0	0.25	0.5	0.75	0	0	0.5	0.75	0	0.25	0	0.25	0	0.25	0.5	0.75	0.75	1	0	0	0.75	1	0	0	0.75	1	0	0.25	0.75	1	0	0	0	0	0.5	0.75	0.5	0.75	0	0.25	0	0.25	0	0.25
CSF19	0.75	1	0.25	0.5	0.5	0.75	0.75	1	0.25	0.5	0.75	1	0.5	0.75	0.5	0.75	0.5	0.75	0.75	1	0.75	1	0.25	0.5	0.75	1	0.25	0.5	0.75	1	0.25	0.5	0.75	1	0.5	0.75	0	0	0.75	1	0.5	0.75	0.5	0.75	0.5	0.75	0.5	0.75
CSF20	0.5	0.75	0	0	0	0.25	0	0.25	0	0	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0.5	0.75	0	0	0.5	0.75	0	0	0.5	0.75	0	0.25	0.5	0.75	0	0.25	0	0	0	0	0.5	0.75	0	0.25	0	0.25	0	0.25
CSF21	0.75	1	0	0	0	0.25	0.5	0.75	0	0	0.5	0.75	0	0.25	0	0.25	0	0.25	0.5	0.75	0.75	1	0	0	0.75	1	0	0	0.75	1	0	0.25	0.75	1	0	0.25	0	0	0.5	0.75	0	0	0	0.25	0	0.25	0	0.25
CSF22	0.75	1	0	0	0	0.25	0.5	0.75	0	0	0.5	0.75	0.25	0.5	0.25	0.5	0.5	0.75	0.75	1	0.75	1	0	0	0.75	1	0	0	0.75	1	0.5	0.75	0.75	1	0.5	0.75	0	0	0.75	1	0.5	0.75	0	0	0	0.25	0	0.25
CSF23	0.75	1	0	0	0	0.25	0.5	0.75	0	0	0.5	0.75	0.25	0.5	0.25	0.5	0.5	0.75	0.75	1	0.75	1	0	0	0.75	1	0	0	0.75	1	0.5	0.75	0.75	1	0.5	0.75	0	0	0.75	1	0.5	0.75	0.25	0.5	0	0	0.25	0.5
CSF24	0.75	1	0	0	0	0.25	0.5	0.75	0	0	0.5	0.75	0.25	0.5	0.25	0.5	0.5	0.75	0.75	1	0.75	1	0	0	0.75	1	0	0	0.75	1	0.5	0.75	0.75	1	0.5	0.75	0	0	0.75	1	0.5	0.75	0.25	0.5	0	0.25	0	0

TABLE IV
DIRECT INFLUENTIAL MATRIX

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10	CSF11	CSF12	CSF13	CSF14	CSF15	CSF16	CSF17	CSF18	CSF19	CSF20	CSF21	CSF22	CSF23	CSF24
CSF1	0.0000	0.0000	0.0625	0.0500	0.0000	0.0500	0.0625	0.0625	0.0625	0.0500	0.0500	0.0000	0.0500	0.0000	0.6500	0.0625	0.0500	0.0625	0.0000	0.0500	0.0625	0.0625	0.0625	0.0625
CSF2	0.9500	0.0000	0.6875	0.9500	0.4167	0.9500	0.6875	0.6875	0.6875	0.9500	0.9500	0.4167	0.9500	0.4167	0.9500	0.3750	0.9500	0.6875	0.1250	0.9500	0.6875	0.6875	0.6875	0.6875
CSF3	0.9500	0.0000	0.0000	0.6500	0.0000	0.6500	0.3750	0.3750	0.6875	0.9500	0.9500	0.0000	0.9500	0.0000	0.9500	0.6875	0.9500	0.6875	0.0000	0.9500	0.6875	0.3750	0.0625	0.0625
CSF4	0.6500	0.0000	0.0625	0.0000	0.0000	0.0500	0.0625	0.0625	0.0625	0.0500	0.6500	0.0000	0.6500	0.0000	0.6500	0.0625	0.6500	0.0625	0.0000	0.6500	0.6875	0.0625	0.0625	0.0625
CSF5	0.9500	0.0833	0.6875	0.9500	0.0000	0.9500	0.6875	0.6875	0.6875	0.9500	0.9500	0.4167	0.9500	0.4167	0.9500	0.3750	0.9500	0.6875	0.1250	0.9500	0.6875	0.6875	0.6875	0.6875
CSF6	0.6500	0.0000	0.0625	0.6500	0.0000	0.0000	0.0625	0.0625	0.0625	0.0500	0.6500	0.0000	0.6500	0.0000	0.6500	0.0625	0.6500	0.0625	0.0000	0.6500	0.6875	0.0625	0.0625	0.0625
CSF7	0.9500	0.0000	0.0625	0.6500	0.0000	0.6500	0.0000	0.0625	0.0625	0.6500	0.9500	0.0000	0.9500	0.0000	0.9500	0.0625	0.9500	0.3750	0.0000	0.6500	0.6875	0.0625	0.0625	0.0625
CSF8	0.9500	0.0000	0.0625	0.6500	0.0000	0.6500	0.3750	0.0000	0.6875	0.9500	0.9500	0.0000	0.9500	0.0000	0.9500	0.6875	0.9500	0.6875	0.0000	0.9500	0.6875	0.0625	0.0625	0.0625
CSF9	0.9500	0.0000	0.0625	0.6500	0.0000	0.6500	0.3750	0.0625	0.0000	0.6500	0.9500	0.0000	0.9500	0.0000	0.9500	0.3750	0.9500	0.3750	0.0000	0.6500	0.6875	0.0625	0.0625	0.0625
CSF10	0.6500	0.0000	0.0625	0.6500	0.0000	0.6500	0.0625	0.0625	0.0625	0.0000	0.6500	0.0000	0.6500	0.0000	0.6500	0.0625	0.6500	0.0625	0.0000	0.6500	0.6875	0.0625	0.0625	0.0625
CSF11	0.6500	0.0000	0.0625	0.0500	0.0000	0.0500	0.0625	0.0625	0.0625	0.0500	0.0000	0.0000	0.0500	0.0000	0.6500	0.0625	0.6500	0.0625	0.0000	0.0500	0.0625	0.0625	0.0625	0.0625
CSF12	0.9500	0.0833	0.6875	0.9500	0.0833	0.9500	0.6875	0.6875	0.6875	0.9500	0.9500	0.0000	0.9500	0.0833	0.9500	0.3750	0.9500	0.6875	0.1250	0.9500	0.6875	0.6875	0.6875	0.6875
CSF13	0.6500	0.0000	0.0625	0.0500	0.0000	0.0500	0.0625	0.0625	0.0625	0.0500	0.6500	0.0000	0.0000	0.0000	0.6500	0.0625	0.6500	0.0625	0.0000	0.0500	0.0625	0.0625	0.0625	0.0625
CSF14	0.9500	0.0833	0.6875	0.9500	0.0833	0.9500	0.6875	0.6875	0.6875	0.9500	0.9500	0.4167	0.9500	0.0000	0.9500	0.3750	0.9500	0.6875	0.1250	0.9500	0.6875	0.6875	0.6875	0.6875
CSF15	0.0500	0.0000	0.0625	0.0500	0.0000	0.0500	0.0625	0.0625	0.0625	0.0500	0.0500	0.0000	0.0500	0.0000	0.0000	0.0625	0.0500	0.0625	0.0000	0.0500	0.0625	0.0625	0.0625	0.0625
CSF16	0.9500	0.0000	0.0625	0.6500	0.0000	0.6500	0.3750	0.0625	0.0625	0.6500	0.9500	0.0000	0.9500	0.0000	0.9500	0.0000	0.9500	0.3750	0.0000	0.6500	0.6875	0.0625	0.0625	0.0625
CSF17	0.6500	0.0000	0.0625	0.0500	0.0000	0.0500	0.0625	0.0625	0.0625	0.0500	0.0500	0.0000	0.0500	0.0000	0.6500	0.0625	0.0000	0.0625	0.0000	0.0500	0.0625	0.0625	0.0625	0.0625
CSF18	0.9500	0.0000	0.0625	0.6500	0.0000	0.6500	0.0625	0.0625	0.0625	0.6500	0.9500	0.0000	0.9500	0.0000	0.9500	0.0625	0.9500	0.0000	0.0000	0.6500	0.6875	0.0625	0.0625	0.0625
CSF19	0.9500	0.4167	0.6875	0.9500	0.4167	0.9500	0.6875	0.6875	0.6875	0.9500	0.9500	0.4167	0.9500	0.4167	0.9500	0.3750	0.9500	0.6875	0.0000	0.9500	0.6875	0.6875	0.6875	0.6875
CSF20	0.6500	0.0000	0.0625	0.0500	0.0000	0.0500	0.0625	0.0625	0.0625	0.0500	0.6500	0.0000	0.6500	0.0000	0.6500	0.0625	0.6500	0.0625	0.0000	0.0000	0.6875	0.0625	0.0625	0.0625
CSF21	0.9500	0.0000	0.0625	0.6500	0.0000	0.6500	0.0625	0.0625	0.0625	0.6500	0.9500	0.0000	0.9500	0.0000	0.9500	0.0625	0.9500	0.0625	0.0000	0.6500	0.0000	0.0625	0.0625	0.0625
CSF22	0.9500	0.0000	0.0625	0.6500	0.0000	0.6500	0.3750	0.3750	0.6875	0.9500	0.9500	0.0000	0.9500	0.0000	0.9500	0.6875	0.9500	0.6875	0.0000	0.9500	0.6875	0.0000	0.0625	0.0625
CSF23	0.9500	0.0000	0.0625	0.6500	0.0000	0.6500	0.3750	0.3750	0.6875	0.9500	0.9500	0.0000	0.9500	0.0000	0.9500	0.6875	0.9500	0.6875	0.0000	0.9500	0.6875	0.3750	0.0000	0.3750
CSF24	0.9500	0.0000	0.0625	0.6500	0.0000	0.6500	0.3750	0.3750	0.6875	0.9500	0.9500	0.0000	0.9500	0.0000	0.9500	0.6875	0.9500	0.6875	0.0000	0.9500	0.6875	0.3750	0.0625	0.0000

a crisp matrix “F” through (1)–(3) as shown in Table IV.

Step 2: The normalized direct relation matrix “S” as shown in Table V has been obtained through (5) and (6).

Step 3: Through (7), the total relation matrix (M) has been determined and shown in Table VI.

Step 4: Developing the causal influence and diagraph diagram in grey DEMATEL requires following two steps.

1) The first step is to determine the sum of rows (D) and the sum of columns (R) from the total relation matrix (*M*) through (8) and (9).

TABLE V
NORMALIZED INFLUENTIAL MATRIX

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10	CSF11	CSF12	CSF13	CSF14	CSF15	CSF16	CSF17	CSF18	CSF19	CSF20	CSF21	CSF22	CSF23	CSF24
CSF1	0.0000	0.0000	0.0032	0.0026	0.0000	0.0026	0.0032	0.0032	0.0032	0.0026	0.0026	0.0000	0.0026	0.0000	0.0334	0.0032	0.0026	0.0032	0.0000	0.0026	0.0032	0.0032	0.0032	0.0032
CSF2	0.0488	0.0000	0.0353	0.0488	0.0214	0.0488	0.0353	0.0353	0.0353	0.0488	0.0488	0.0214	0.0488	0.0214	0.0488	0.0193	0.0488	0.0353	0.0064	0.0488	0.0353	0.0353	0.0353	0.0353
CSF3	0.0488	0.0000	0.0000	0.0334	0.0000	0.0334	0.0193	0.0193	0.0353	0.0488	0.0488	0.0000	0.0488	0.0000	0.0488	0.0353	0.0488	0.0353	0.0000	0.0488	0.0353	0.0193	0.0032	0.0032
CSF4	0.0334	0.0000	0.0032	0.0000	0.0000	0.0026	0.0032	0.0032	0.0032	0.0026	0.0334	0.0000	0.0334	0.0000	0.0334	0.0032	0.0334	0.0032	0.0000	0.0334	0.0353	0.0032	0.0032	0.0032
CSF5	0.0488	0.0043	0.0353	0.0488	0.0000	0.0488	0.0353	0.0353	0.0353	0.0488	0.0488	0.0214	0.0488	0.0214	0.0488	0.0193	0.0488	0.0353	0.0064	0.0488	0.0353	0.0353	0.0353	0.0353
CSF6	0.0334	0.0000	0.0032	0.0334	0.0000	0.0000	0.0032	0.0032	0.0032	0.0026	0.0334	0.0000	0.0334	0.0000	0.0334	0.0032	0.0334	0.0032	0.0000	0.0334	0.0353	0.0032	0.0032	0.0032
CSF7	0.0488	0.0000	0.0032	0.0334	0.0000	0.0334	0.0000	0.0032	0.0032	0.0334	0.0488	0.0000	0.0488	0.0000	0.0488	0.0032	0.0488	0.0193	0.0000	0.0334	0.0353	0.0032	0.0032	0.0032
CSF8	0.0488	0.0000	0.0032	0.0334	0.0000	0.0334	0.0193	0.0000	0.0353	0.0488	0.0488	0.0000	0.0488	0.0000	0.0488	0.0353	0.0488	0.0353	0.0000	0.0488	0.0353	0.0032	0.0032	0.0032
CSF9	0.0488	0.0000	0.0032	0.0334	0.0000	0.0334	0.0193	0.0032	0.0000	0.0334	0.0488	0.0000	0.0488	0.0000	0.0488	0.0193	0.0488	0.0193	0.0000	0.0334	0.0353	0.0032	0.0032	0.0032
CSF10	0.0334	0.0000	0.0032	0.0334	0.0000	0.0334	0.0032	0.0032	0.0032	0.0000	0.0334	0.0000	0.0334	0.0000	0.0334	0.0032	0.0334	0.0032	0.0000	0.0334	0.0353	0.0032	0.0032	0.0032
CSF11	0.0334	0.0000	0.0032	0.0026	0.0000	0.0026	0.0032	0.0032	0.0032	0.0026	0.0000	0.0000	0.0026	0.0000	0.0334	0.0032	0.0334	0.0032	0.0000	0.0026	0.0032	0.0032	0.0032	0.0032
CSF12	0.0488	0.0043	0.0353	0.0488	0.0043	0.0488	0.0353	0.0353	0.0353	0.0488	0.0488	0.0000	0.0488	0.0043	0.0488	0.0193	0.0488	0.0353	0.0064	0.0488	0.0353	0.0353	0.0353	0.0353
CSF13	0.0334	0.0000	0.0032	0.0026	0.0000	0.0026	0.0032	0.0032	0.0032	0.0026	0.0334	0.0000	0.0000	0.0000	0.0334	0.0032	0.0334	0.0032	0.0000	0.0026	0.0032	0.0032	0.0032	0.0032
CSF14	0.0488	0.0043	0.0353	0.0488	0.0043	0.0488	0.0353	0.0353	0.0353	0.0488	0.0488	0.0214	0.0488	0.0000	0.0488	0.0193	0.0488	0.0353	0.0064	0.0488	0.0353	0.0353	0.0353	0.0353
CSF15	0.0026	0.0000	0.0032	0.0026	0.0000	0.0026	0.0032	0.0032	0.0032	0.0026	0.0026	0.0000	0.0026	0.0000	0.0000	0.0032	0.0026	0.0032	0.0000	0.0026	0.0032	0.0032	0.0032	0.0032
CSF16	0.0488	0.0000	0.0032	0.0334	0.0000	0.0334	0.0193	0.0032	0.0032	0.0334	0.0488	0.0000	0.0488	0.0000	0.0488	0.0000	0.0488	0.0193	0.0000	0.0334	0.0353	0.0032	0.0032	0.0032
CSF17	0.0334	0.0000	0.0032	0.0026	0.0000	0.0026	0.0032	0.0032	0.0032	0.0026	0.0026	0.0000	0.0026	0.0000	0.0334	0.0032	0.0000	0.0032	0.0000	0.0026	0.0032	0.0032	0.0032	0.0032
CSF18	0.0488	0.0000	0.0032	0.0334	0.0000	0.0334	0.0032	0.0032	0.0032	0.0334	0.0488	0.0000	0.0488	0.0000	0.0488	0.0032	0.0488	0.0000	0.0000	0.0334	0.0353	0.0032	0.0032	0.0032
CSF19	0.0488	0.0214	0.0353	0.0488	0.0214	0.0488	0.0353	0.0353	0.0353	0.0488	0.0488	0.0214	0.0488	0.0214	0.0488	0.0193	0.0488	0.0353	0.0000	0.0488	0.0353	0.0353	0.0353	0.0353
CSF20	0.0334	0.0000	0.0032	0.0026	0.0000	0.0026	0.0032	0.0032	0.0032	0.0026	0.0334	0.0000	0.0334	0.0000	0.0334	0.0032	0.0334	0.0032	0.0000	0.0000	0.0353	0.0032	0.0032	0.0032
CSF21	0.0488	0.0000	0.0032	0.0334	0.0000	0.0334	0.0032	0.0032	0.0032	0.0334	0.0488	0.0000	0.0488	0.0000	0.0488	0.0032	0.0488	0.0032	0.0000	0.0334	0.0000	0.0032	0.0032	0.0032
CSF22	0.0488	0.0000	0.0032	0.0334	0.0000	0.0334	0.0193	0.0193	0.0353	0.0488	0.0488	0.0000	0.0488	0.0000	0.0488	0.0353	0.0488	0.0353	0.0000	0.0488	0.0353	0.0000	0.0032	0.0032
CSF23	0.0488	0.0000	0.0032	0.0334	0.0000	0.0334	0.0193	0.0193	0.0353	0.0488	0.0488	0.0000	0.0488	0.0000	0.0488	0.0353	0.0488	0.0353	0.0000	0.0488	0.0353	0.0193	0.0000	0.0193
CSF24	0.0488	0.0000	0.0032	0.0334	0.0000	0.0334	0.0193	0.0193	0.0353	0.0488	0.0488	0.0000	0.0488	0.0000	0.0488	0.0353	0.0488	0.0353	0.0000	0.0488	0.0353	0.0193	0.0032	0.0000

2) In the next step, the influential diagraph has been set up through the *x* and *y* axes formed with D+R and D-R. Further with these axes, cause and effect group relationships were analyzed.

C. Phase III: Results and Validation

As discussed earlier, this study seeks to minimize the bias of data inputs and to maximize the reliability of the results. In the process, any bias of the data was minimized through the grey approach; further, to maximize reliability, this article considers three-way feedback. It includes feedback from case managers, experts, and state-of-the-art resources. Based on this three-way feedback, the results are validated.

VI. RESULTS AND DISCUSSION

This section intends to analyze the obtained results through series of literature acknowledgments and feedback from case decision makers. Table VII shows the sum of rows and sum of columns, which are further used to draw a diagraph as shown in Fig. 2. In this article, about 24 CSFs were considered and further the same has been categorized into 6 sustainable frugal innovation dimensions. Based on the diagraph, the most and least influential CSFs have been identified.

For a better understanding, the diagraph has been modified into Table VIII, in which the CSFs are categorized into two groups: 1) cause or 2) effect. Detailed discussions on both groups are as follows.

A. Cause Group

Among 24 collected CSFs, 13 CSFs are positioned in the cause group. The criteria/CSFs that reside in the cause group have influence on other criteria/CSFs, which do not exist in the cause group. Among these 13 CSFs, the most influential CSF is identified as "Understanding the concept of AI" (**CSF 19**), followed by "Level of AI investment" (**CSF 2**). Contrary to this, the least influential CSFs under the cause group are registered as "Health and safety" (**CSF 7**) and "Identification of AI partners" (**CSF 16**). The remaining influential rankings of CSFs under the cause group are as follows: CSF 19 > CSF 2 > CSF 5 > CSF 14 > CSF 12 > CSF 23 > CSF 24 > CSF 3 > CSF 22 > CSF 8 > CSF 9 > CSF 16 > CSF 7. The high number of cause group CSFs can be seen under the dimension of "technological frugal innovation" with four CSFs (**CSF 19, CSF 22, CSF 23, CSF 24**), which is followed by "social frugal innovation" with three CSFs (**CSF 7, CSF 8, CSF 9**); all reside in the cause group.

B. Effect Group

Among 24 collected CSFs, 11 CSFs are positioned in the effect group. The criteria/CSFs that comprise the effect group are the influenced criteria/CSFs by other criteria/CSFs, which do not exist in the effect group. Among these 11 CSFs, the least influential CSF is identified as "Communication" (**CSF 15**), followed by "Promotion, incentives, policy support from government" (**CSF 1**). Contrary to this, the least influential CSFs under the effect group are registered as "Supply team facilitation" (**CSF 18**), and "Data quality and protection" (**CSF 21**). The remaining influential rankings of CSFs under effect group are as follows: CSF 18 > CSF 21 > CSF 10 > CSF 6 > CSF 4 > CSF 20 > CSF 13 > CSF 11 > CSF 17 > CSF 1 > CSF 15. The high number of effect group CSFs can be seen under the dimension of "Operational frugal innovation" with two CSFs positioned under effect group; next to that, "Supply chain frugal innovation" (**CSF 17** and **CSF 18**) and "Technological frugal innovation" (**CSF 20** and **CSF 21**) both have two CSFs that fall under the effect group. However, concerning these two dimensions, it can be

TABLE VI
TOTAL INFLUENTIAL MATRIX

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10	CSF11	CSF12
CSF1	0.0032	0.0000	0.0036	0.0044	0.0000	0.0042	0.0040	0.0038	0.0042	0.0044	0.0054	0.0000
CSF2	**0.0937**	0.0004	0.0417	**0.0739**	0.0218	**0.0717**	0.0464	0.0444	0.0486	**0.0727**	**0.0882**	0.0225
CSF3	**0.0760**	0.0000	0.0027	0.0466	0.0000	0.0452	0.0241	0.0225	0.0398	**0.0597**	**0.0715**	0.0000
CSF4	0.0434	0.0000	0.0043	0.0038	0.0000	0.0062	0.0048	0.0046	0.0050	0.0063	0.0409	0.0000
CSF5	**0.0922**	0.0046	0.0410	**0.0726**	0.0004	**0.0705**	0.0456	0.0437	0.0477	**0.0715**	**0.0867**	0.0221
CSF6	0.0448	0.0000	0.0044	0.0372	0.0000	0.0038	0.0050	0.0047	0.0052	0.0065	0.0421	0.0000
CSF7	**0.0658**	0.0000	0.0051	0.0405	0.0000	0.0393	0.0025	0.0054	0.0059	0.0385	**0.0619**	0.0000
CSF8	**0.0736**	0.0000	0.0057	0.0452	0.0000	0.0438	0.0234	0.0029	0.0386	**0.0578**	**0.0693**	0.0000
CSF9	**0.0679**	0.0000	0.0052	0.0418	0.0000	0.0406	0.0221	0.0056	0.0029	0.0398	**0.0639**	0.0000
CSF10	0.0461	0.0000	0.0046	0.0384	0.0000	0.0372	0.0051	0.0049	0.0053	0.0041	0.0434	0.0000
CSF11	0.0378	0.0000	0.0038	0.0046	0.0000	0.0045	0.0042	0.0040	0.0044	0.0047	0.0032	0.0000
CSF12	**0.0891**	0.0045	0.0396	**0.0702**	0.0045	**0.0681**	0.0441	0.0422	0.0461	**0.0691**	**0.0838**	0.0004
CSF13	0.0389	0.0000	0.0039	0.0048	0.0000	0.0046	0.0044	0.0042	0.0046	0.0048	0.0366	0.0000
CSF14	**0.0906**	0.0045	0.0403	**0.0714**	0.0046	**0.0693**	0.0449	0.0429	0.0469	**0.0703**	**0.0853**	0.0218
CSF15	0.0056	0.0000	0.0035	0.0042	0.0000	0.0041	0.0039	0.0037	0.0040	0.0042	0.0053	0.0000
CSF16	**0.0669**	0.0000	0.0052	0.0412	0.0000	0.0399	0.0217	0.0055	0.0060	0.0391	**0.0629**	0.0000
CSF17	0.0366	0.0000	0.0037	0.0045	0.0000	0.0044	0.0041	0.0039	0.0043	0.0045	0.0056	0.0000
CSF18	**0.0648**	0.0000	0.0050	0.0399	0.0000	0.0387	0.0056	0.0053	0.0058	0.0379	**0.0610**	0.0000
CSF19	**0.0951**	0.0217	0.0423	**0.0750**	0.0221	**0.0727**	0.0471	0.0451	0.0493	**0.0738**	**0.0895**	0.0229
CSF20	0.0421	0.0000	0.0042	0.0062	0.0000	0.0060	0.0047	0.0045	0.0049	0.0061	0.0397	0.0000
CSF21	**0.0628**	0.0000	0.0048	0.0386	0.0000	0.0375	0.0054	0.0052	0.0056	0.0367	**0.0591**	0.0000
CSF22	**0.0748**	0.0000	0.0058	0.0459	0.0000	0.0445	0.0238	0.0221	0.0392	**0.0587**	**0.0704**	0.0000
CSF23	**0.0772**	0.0000	0.0060	0.0474	0.0000	0.0459	0.0245	0.0229	0.0405	**0.0606**	**0.0726**	0.0000
CSF24	**0.0760**	0.0000	0.0059	0.0466	0.0000	0.0452	0.0241	0.0225	0.0398	**0.0597**	**0.0715**	0.0000

	CSF13	CSF14	CSF15	CSF16	CSF17	CSF18	CSF19	CSF20	CSF21	CSF22	CSF23	CSF24
CSF1	0.0053	0.0000	0.0366	0.0042	0.0056	0.0044	0.0000	0.0048	0.0053	0.0037	0.0036	0.0036
CSF2	**0.0856**	0.0221	**0.0966**	0.0321	**0.0909**	0.0506	0.0069	**0.0794**	**0.0638**	0.0437	0.0417	0.0424
CSF3	**0.0694**	0.0000	**0.0783**	0.0405	**0.0737**	0.0415	0.0000	**0.0643**	0.0514	0.0221	0.0059	0.0060
CSF4	0.0397	0.0000	0.0448	0.0051	0.0421	0.0053	0.0000	0.0376	0.0394	0.0045	0.0043	0.0044
CSF5	**0.0841**	0.0218	**0.0950**	0.0316	**0.0894**	0.0497	0.0067	**0.0781**	**0.0627**	0.0430	0.0410	0.0417
CSF6	0.0409	0.0000	0.0461	0.0053	0.0434	0.0054	0.0000	0.0387	0.0406	0.0047	0.0044	0.0045
CSF7	**0.0601**	0.0000	**0.0678**	0.0060	**0.0639**	0.0222	0.0000	0.0422	0.0443	0.0053	0.0051	0.0052
CSF8	**0.0672**	0.0000	**0.0758**	0.0392	**0.0714**	0.0402	0.0000	**0.0623**	0.0498	0.0060	0.0057	0.0058
CSF9	**0.0620**	0.0000	**0.0700**	0.0222	**0.0659**	0.0229	0.0000	0.0435	0.0457	0.0055	0.0052	0.0053
CSF10	0.0421	0.0000	0.0476	0.0054	0.0448	0.0056	0.0000	0.0399	0.0419	0.0048	0.0046	0.0047
CSF11	0.0056	0.0000	0.0389	0.0045	0.0366	0.0046	0.0000	0.0051	0.0056	0.0040	0.0038	0.0039
CSF12	**0.0813**	0.0046	**0.0918**	0.0305	**0.0864**	0.0481	0.0065	**0.0755**	**0.0606**	0.0416	0.0396	0.0403
CSF13	0.0032	0.0000	0.0401	0.0046	0.0378	0.0048	0.0000	0.0052	0.0058	0.0041	0.0039	0.0040
CSF14	**0.0827**	0.0004	**0.0934**	0.0311	**0.0879**	0.0489	0.0066	**0.0768**	**0.0617**	0.0423	0.0403	0.0410
CSF15	0.0051	0.0000	0.0032	0.0041	0.0054	0.0042	0.0000	0.0046	0.0051	0.0036	0.0035	0.0035
CSF16	**0.0611**	0.0000	**0.0689**	0.0029	**0.0649**	0.0225	0.0000	0.0428	0.0450	0.0054	0.0052	0.0052
CSF17	0.0054	0.0000	0.0378	0.0044	0.0032	0.0045	0.0000	0.0049	0.0054	0.0039	0.0037	0.0037
CSF18	**0.0592**	0.0000	**0.0668**	0.0059	**0.0628**	0.0029	0.0000	0.0415	0.0436	0.0052	0.0050	0.0051
CSF19	**0.0869**	0.0225	**0.0981**	0.0326	**0.0923**	0.0513	0.0006	**0.0806**	**0.0647**	0.0444	0.0423	0.0430
CSF20	0.0385	0.0000	0.0434	0.0049	0.0409	0.0051	0.0000	0.0041	0.0382	0.0044	0.0042	0.0043
CSF21	**0.0573**	0.0000	**0.0647**	0.0057	**0.0609**	0.0059	0.0000	0.0402	0.0081	0.0051	0.0048	0.0049
CSF22	**0.0683**	0.0000	**0.0771**	0.0398	**0.0725**	0.0408	0.0000	**0.0633**	0.0506	0.0029	0.0058	0.0059
CSF23	**0.0705**	0.0000	**0.0796**	0.0411	**0.0749**	0.0422	0.0000	**0.0654**	0.0522	0.0225	0.0028	0.0221
CSF24	**0.0694**	0.0000	**0.0783**	0.0405	**0.0737**	0.0415	0.0000	**0.0643**	0.0514	0.0221	0.0059	0.0028

TABLE VII
SUM OF ROWS AND SUM OF COLUMNS

Succes factors		D	R	D+R	D-R
Promotion, incentives, policy support from government	**CSF1**	0.1141	1.4649	1.5790	-1.3507
Level of AI investment	**CSF2**	1.2818	0.0358	1.3176	1.2460
Green production support (9R)	**CSF3**	0.8412	0.2924	1.1336	0.5489
Reduced cycle/response time	**CSF4**	0.3464	0.9048	1.2512	-0.5584
Multi functionalities/upcycling	**CSF5**	1.2435	0.0535	1.2970	1.1901
Environmental performance measurement (value chain)	**CSF6**	0.3879	0.8479	1.2358	-0.4601
Health and Safety	**CSF7**	0.5870	0.4458	1.0328	0.1413
Privacy management	**CSF8**	0.7837	0.3765	1.1601	0.4072
Transparency	**CSF9**	0.6383	0.5047	1.1430	0.1336
Resilience alert	**CSF10**	0.4306	0.8917	1.3223	-0.4612
Performance evaluation	**CSF11**	0.1838	1.3199	1.5037	-1.1362
Training of employees	**CSF12**	1.1689	0.0897	1.2586	1.0792
Centralized decision making	**CSF13**	0.2202	1.2507	1.4709	-1.0305
Top management support	**CSF14**	1.2059	0.0714	1.2773	1.1344
Communication	**CSF15**	0.0809	1.5407	1.6216	-1.4598
Identification of AI partners	**CSF16**	0.6124	0.4443	1.0567	0.1682
Vendor support and cooperation on SFI	**CSF17**	0.1484	1.3913	1.5397	-1.2429
Supply team facilitation	**CSF18**	0.5620	0.5751	1.1371	-0.0131
Understanding the concept of AI	**CSF19**	1.3158	0.0273	1.3431	1.2885
Value chain technology supporting facilities	**CSF20**	0.3062	1.0654	1.3716	-0.7591
Data quality and protection	**CSF21**	0.5135	0.9429	1.4564	-0.4293
Integrated data warehouses	**CSF22**	0.8122	0.3548	1.1670	0.4574
Technology readiness	**CSF23**	0.8707	0.2924	1.1631	0.5784
Analytics capabilities	**CSF24**	0.8412	0.3131	1.1543	0.5282

TABLE VIII
INFLUENTIAL CSFS FOR AI ADAPTION IN SUSTAINABLE FRUGAL INNOVATION

Dimensions of sustainable frugal innovation		CSF for AI adaption in sustainable frugal innovation		Position of influence
Economical frugal innovation	D1	Promotion, incentives, policy support from government	CSF1	Effect
		Level of AI investment	CSF2	Cause
Environmental frugal innovation	D2	Green production support (9R)	CSF3	Cause
		Reduced cycle/response time	CSF4	Effect
		Multi functionalities/upcycling	CSF5	Cause
		Environmental performance measurement (value chain)	CSF6	Effect
Social frugal innovation	D3	Health and Safety	CSF7	Cause
		Privacy management	CSF8	Cause
		Transparency	CSF9	Cause
		Resilience alert	CSF10	Effect
Operational frugal innovation	D4	Performance evaluation	CSF11	Effect
		Training of employees	CSF12	Cause
		Centralized decision making	CSF13	Effect
		Top management support	CSF14	Cause
		Communication	CSF15	Effect
Supply chain frugal innovation	D5	Identification of AI partners	CSF16	Cause
		Vendor support and cooperation on SFI	CSF17	Effect
		Supply team facilitation	CSF18	Effect
Technological frugal innovation	D6	Understanding the concept of AI	CSF19	Cause
		Value chain technology supporting facilities	CSF20	Effect
		Data quality and protection	CSF21	Effect
		Integrated data warehouses	CSF22	Cause
		Technology readiness	CSF23	Cause
		Analytics capabilities	CSF24	Cause

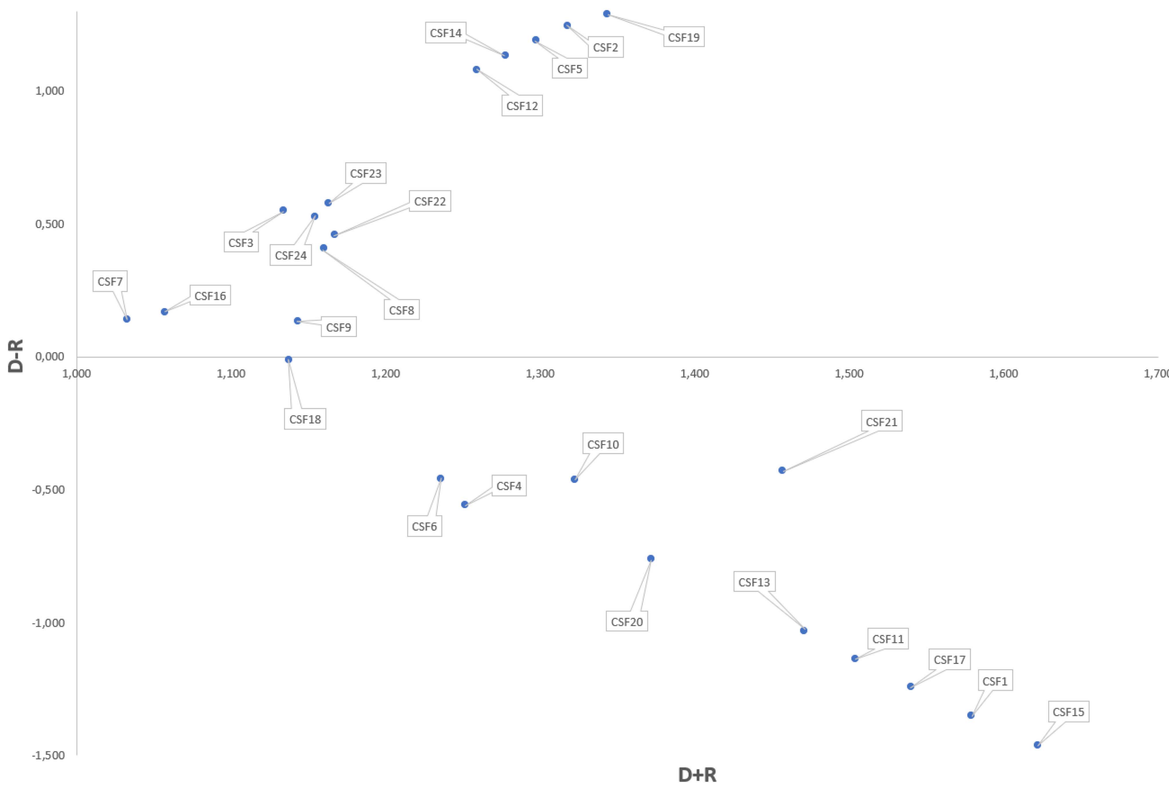

Fig. 2. Influential diagraph.

argued that the "Supply chain frugal innovation" dimension is the one which is more influenced by other dimensions because, among the four CSFs in this dimension, two CSFs fall under the effect group (equivalent to two-thirds of the factors), whereas in "Technological frugal innovation," only two of the six CSFs are under the effect group.

Overall, from the above results, it has been determined that the most influential CSFs are **CSF 19** and **CSF 2**. The most influential dimension has been identified as "**Technological frugal innovation**." On the other hand, the least influential CSFs are **CSF 15** and **CSF 1**, whereas, with the concern of dimension, the least influential is "**Operational frugal innovation**." Once the results are clearly listed, then the study initiated its three-way feedback mechanism. The first step in this mechanism is to explore the results with the concern of the literature's perspective. The literature review reveals that obtained results are acknowledged with other existing studies and theories. For instance, innovation often faces several challenges including rival technologies, volatile markets, the growth of competitive businesses, demanding stakeholders, and changing landscapes [42], [72]. This makes the innovation process more difficult; hence, it is necessary for AI to understand the complexity of the innovation process. The firm must understand the basics of AI to exactly address the challenges of the innovation process. The challenges of the innovation process are even higher in proposed sustainable frugal innovation, so managers need to understand the basic structure of AI, which could further assist them to appropriately adopt sustainable frugal innovation in the areas with the greatest need. In addition, the application and adoption of AI vastly differ with the application, so it is necessary to correlate the basics of AI with the field of application. This statement was acknowledged by Chen *et al.* [21] in their article that says AI adoption differs with organizational capability and the firm's environmental circumstances. These discussions prove that understanding AI on sustainable frugal innovation is the most influential success factor. Next, this study claims that the "level of AI investment" is the most influential factor despite many studies that categorize this factor as a barrier to AI adaption. In nature, frugal innovation works on the principle of operating with less expensive resources; in contrast, AI adoption generally increases the operating cost. Hence, managers are more likely to balance the level of AI investment to effectively adopt AI in sustainable frugal innovation. However, if this AI investment balances more effectively, then it drives AI adaption faster than other factors. For instance, Cubric [23] argued that most of the drivers of AI adoption are from economic pillars. Finally, this study reveals that "communication" is the least influential CSF; even in many conventional cases, it is clear that communication is an effective tool for implementation. But in the technology era, communication is not a concern. Data reliability is a concern, so this study's results show communication as a less influential factor for AI adoption in sustainable frugal innovation.

For an effective understanding of the most influential drivers, it is necessary to interrelate the influential driver with other influenced drivers. This relation has been obtained through Table VI, in which, based on the threshold values (0.055), the relation of influential driver "Understanding the concept of AI" (CSF 19) with other drivers (CSF 1, CSF 4, CSF 6, CSF 10, CSF 11, CSF 13, CSF 15, CSF 17, CSF 20, and CSF 21). The discussion on these relations has been shared based on their dimensions in the upcoming sections.

Among the first dimension, "Economical frugal innovation," the influential driver (CSF 19) influences "Promotion, incentives, policy support from government" (CSF 1). Frugal innovation is not only beneficial to the firms financially; it also helps the society and environment to achieve sustainable advantages through the principles of frugal innovation. Hence, there is substantial responsibility for the government to promote such sustainable frugal innovation through AI. According to a 2016 Statista survey, nearly 80% of companies believed that the implementation of AI could bring new opportunities and increase their existing capabilities for a competitive business environment [64]. Despite these advantages, some companies remain hesitant to adopt AI in their applications, including sustainable frugal innovation, due to the high capital involved in the AI implementation process. To tackle such a high initial cost for AI adoption in sustainable frugal innovation, it is necessary to secure external financial support such as from government agencies, NGOs, and so on. Hence, CSF 1 is placed under the dimension of economical frugal innovation. Despite the impetus, governmental agencies are not much interested in such AI-related developments, largely due to the lack of knowledge on that AI application (sustainable frugal innovation). Even the government sectors are less interested in implementing AI in public services, and according to studies by Aoki [7], Wirtz *et al.* [95], and Zuiderwijk *et al.* [107], the biggest challenge among the government agencies for the implementation of AI is a knowledge gap. This knowledge gap hinders government agencies from implementing AI in their own context and it makes them reject decisions for financial support that would allow other companies to adopt AI measures. This verifies that "Understanding the concept of AI" (CSF 19) influences the "Promotion, incentives, policy support from government" (CSF 1).

The second dimension considered for the classification of drivers is "Environmental frugal innovation"; this influential driver CSF 19 impacts two drivers ("Reduced cycle/ response time," CSF 4 and "Environmental performance measurement (value chain)," CSF 6) under this dimension. In May 2021, a report was published on behalf of the European commission entitled "The role of artificial intelligence in the European green deal." This article outlined several potential benefits of AI with the concern of green development [37]. As per the report, regardless of the application sector, AI could provide greater benefits for the application company. Contrary to this, the report claims that a negative environmental effect could occur from the implementation of AI due to a rise in infrastructures, including data centers and networks. Such developments need proper steering on the concept of AI with the respect to green activities, including CSF 4 and CSF 6. Furthermore, the current trend of overlooking environmental dimension concepts with the principle of AI adoption increases the risks of a potential gap. Hence, increasing the understanding of the AI concept could lead to effective implementation of frugal innovation with green concerns as stated by the European Commission.

Social frugal innovation serves as the third dimension of this study for the drivers of AI adoption in sustainable frugal innovation. Under this dimension, only one driver ("Resilience alert" CSF 10) has been influenced by the influential driver (CSF 19). Several studies affirm that there is a strong correlation between AI adoption and sustainable advantage; for instance, Vinuesa *et al.* [90] claim that AI acts as an enabler and an inhibitor for SDGs achievement. Specifically, this study highlights that SDG 4, SDG 6, and SDG 7 draws 100% positive impacts due to the adoption of AI. "Resilience alert" (CSF 10) is one of the key functions for the society while having sustainable frugal innovation as a main concern. Sustainable frugal innovation often comes into play when there is an emergency, and all resources are not effective to use. In such cases, resilience alert systems can assist the companies to use fewer resources to predict emergency situations and then to react to them accordingly. Hence, CSF 10 is considered a key driver under the social dimension, although resilience alerts differ from situation to situation. There are several social emergencies that might occur within a firm, so a good understanding of the application of AI with the corresponding emergencies is needed. In China, AI has been used to track human movements to be resilient before an emergency [18]. This kind of application needs different components of AI, whereas a natural disaster needs something different. To understand these differences and to implement the AI as an effective resilience alert, it is mandated to recognize the underlying concepts of AI; hence, CSF 19 influences CSF 10 under this social frugal innovation dimension.

Among other considered dimensions, Entrepreneurial (operational) frugal innovation has a greater number of influenced drivers (CSF 11, CSF 13, and CSF 17) by CSF 19. Globally, entrepreneurs are always tending to adopt AI even with sustainable frugal innovation applications. According to the survey, "Leadership in AI 2021," nearly 73% of entrepreneurs wanted to implement AI in the next 12 months. However, nearly 63% of the respondents are not aware of the AI adoption process [17]. It might be due to several issues involved in the implementation, but a central point is that entrepreneurs are generally not aware of the performances of adopting AI (CSF 11) in areas other than economics. This confusion affects the entrepreneurs' decision making (CSF 13) on the AI investments and resources allocations. Due to their lack of awareness on performance and their lack of solid decision making, among the operational partners, communication (CSF 15) becomes tedious. All these influential drivers are aligned with one focus, knowledge on the performance; however, to understand the AI performance measurement, it is necessary to understand the concepts of AI, which has even been mentioned by *Forbes* magazine [36] as "Lack of intelligence about AI." Hence, it can be argued that CSF 19 potentially drives the other drivers (CSF 11, CSF 13, and CSF 17) of "Entrepreneurial (operational) frugal innovation."

The implication of AI in the application of supply chain has been gained more momentum in recent years, which is also reflected in the results that show the influential driver (CSF 19) has influence on "Vendor support and cooperation on sustainable frugal innovation" (CSF 20). Usually, companies have a network of suppliers/vendors who maintain an abundance of data, and this data permits effective decisions to be reached. Under such circumstances, AI has been used to smooth the data flow, a process that includes tracking. Vendors must be willing to engage in AI-based operations for a healthy adoption of AI; those operations will likely include the application of sustainable frugal innovation. Several studies [32], [77] confirm that if stakeholders are willing to play a vital role in AI adoption, vendors—one of the strong stakeholders—must meet the intention for successful AI adoption. A lack of understanding of the concepts of AI forces the vendors to demonstrate insufficient willingness toward AI adoption. Therefore "understanding of AI concept" influences "Vendor support and cooperation on sustainable frugal innovation" (CSF 20) under the "supply chain frugal innovation" dimension.

Finally, the influential driver (CSF 19) has influences on two drivers (CSF 20 and CSF 21) in its own dimension, "Technological frugal innovation." AI environment is continuously evolving, and this evolution makes AI more complex in terms of its infrastructure. The main infrastructure of AI generally consists of network facilities, where data from different value chain actors are managed. Hence, to tackle such complex and evolving systems, network facilities should be precise in supporting the value chain actors involved. Because of this significance, (CSF 20) has been considered as one of the most important factors of AI adoption of sustainable frugal innovation. Such network facilities become better with the quality of available data. According to the estimation of IBM in 2017, nearly 90% of global data has been generated within 2 years [96]. This shows the significance of handling data because the data quality is key for effective decision making, including the implementation of sustainable frugal innovation. Furthermore, protecting such quality data is another essential task for the technology managers involved in AI implementation. The data might be sensitive, copyrighted, or based on national security. Accordingly, studies by Andrasko *et al.* [6] and Ntoutsi *et al.* [71] suggest the quality of data and protection as a key driver for AI implementation. For effective data quality and protection, companies must understand the basic concepts of AI within the application (such as sustainable frugal innovation). According to the survey by Mindtree on 650 IT company officials, nearly 85% of respondents does not have any conceptual knowledge of AI related to the data generated; this gap even becomes harder for the applications apart from sales and marketing [11]. This conceptual knowledge of AI (CSF 19) influences the data quality and protection (CSF 21) along with network supporting facilities (CSF 20) under the "Technological frugal innovation" dimension. Nearly all the results are acknowledged by the existing studies, so it is time for the next stage of validation.

In this validation step, feedback from field experts and case decision managers was considered. For this, a one-day workshop was held for the data collection. In this workshop, the results were circulated to the participants to understand their opinions. The research group held a roundtable conference to present the results, where questions from experts and case decision makers were answered. After many rounds of discussion, the results were accepted by field experts and case management leaders. Most of the participants were mildly shocked by the dimension-oriented results, in which, particularly, the "operational frugal innovation" dimension is identified as the least influential. Few participants (including a case decision maker) contradicted this finding, but through the rationale, it was finally resolved; eventually, all participants validated the end results. In this process of justification, participants were introduced to the difference between the conventional systems with modern technical systems (AI) along with the uniqueness of sustainable frugal innovation. Results were validated through a review of the literature and statements from both the experts and the case decision makers.

VII. Conclusion, Implications, Recommendations, and Future Research Agenda

Increasing R&D costs and the recent pandemic have forced industries to work under economic pressure, and that pressure has motivated thinking of new innovation strategies. This focus brought frugal innovation into the spotlight. As a long-term strategy, industries need to engage this frugal innovation thinking in a sustainable way. Therefore, sustainable frugal innovation has become a hot topic in recent years despite little attention to the concept in the research literature. To address this gap, this article proposed an effective implementation of sustainable frugal innovation through technology, AI. To adopt AI to sustainable frugal innovation, it is necessary to understand the CSFs for AI adoption. This article proposed a research framework for the identification and analysis of the CSFs, the categorization of considered common CSFs has been concluded through different theories, including TBL theory, DOI theory, and CSF theory. With the help of a Danish case study context, the proposed framework has been validated, where CSFs were analyzed through the grey DEMATEL approach. The results show that among the collected 24 CSFs under 6 dimensions, "understanding the concept of AI" has been found as the most influential factor for AI adoption in sustainable frugal innovation. In addition, among the five considered dimensions, it has been shown that the "technological frugal innovation" dimension has a large number of influential CSFs, which clearly shows that this dimension has the most influence on other dimensions in AI adoption.

Although this article has several managerial implications, the key implication is a new introduction of knowledge on adopting AI in sustainable frugal innovation. This knowledge could make top management understand the need for sustainable frugal innovation and the means by which to further implement it effectively through AI adoption. In addition, this article reduces the time and skills required to identify the success factors that are effective in AI customization. This article clearly highlights the influential success factors along with dimensions that can help managers optimize their use of resources and skills to address the influential factors and dimensions.

However, in order to effectively motivate the influential CSFs, specific practices should be followed. This article highlights that "understanding the concept of AI" and "level of AI investment" are the most influential success factors; therefore, specific practices need to be designed to successfully motivate these factors to effectively adopt AI to sustainable frugal innovation. The main approaches include training employees and top-level management through attending workshops and seminars or by reading technical papers. This type of training can improve the understanding of AI in the field of sustainable frugal innovation, which can further assist managers in their decision-making and may correspondingly reduce investment in AI. In addition, the training program allows leaders to integrate AI technology into selectively optimized sustainable frugal innovation practices.

Although there are several scientific contributions from this article, the results can be seen as groundbreaking work to integrate AI with sustainable frugal innovation. Still, however, there are limitations. The biggest limitation is that this article looks at only a single case industry, and the results are depicted based on the case managers' decisions, which may be different from other industries. Therefore, a statistical approach or several case studies are needed to validate the results obtained. For a pilot study and groundbreaking perspective, the current study is enough. With the implementation of the practitioner's level, several different statistical validations are needed. This approach may be an opportunity for future researchers to explore more about improving sustainable frugal innovation through effective AI adoption. Furthermore, this article limits its view to a generic level of exploring entrepreneurship opportunities associated with sustainable frugal innovation. Hence, there is a need for more studies to understand the correlations that exist and how such attempts could assist the entrepreneurs to improve their innovation in their firms by integrating sustainable frugal innovation.

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