APPLICATION OF THE SET BASED CONCURRENT ENGINEERING (SBCE) PROCESS: A SYSTEMATIC LITERATURE REVIEW

Muhammad Syafiq bin Shaharudin, Muhd Ikmal Isyraf bin Mohd Maulana*, Abdillah Sani bin Mohd Najib, Aini Zuhra binti Abdul Kadir, Saiful Anuar bin Abu Bakar

Faculty of Mechanical Engineering Universiti Teknologi Malaysia 81310 UTM Johor Bahru Johor, Malaysia.

*Corresponding email: muhdikmalisyraf@utm.my

Article history
Received
3rd June 2025
Revised
4th October 2025
Accepted
19th October 2025
Published
1st December 2025

ABSTRACT

The purpose of this paper is to document a comprehensive review of the application of set based concurrent engineering (SBCE) in industries. Additionally, it aims to investigate the integrated technologies within the domain of SBCE applications and identify research gaps in the corresponding technological landscape. An in-depth examination of 48 research papers provides valuable insights into SBCE's application in a variety of industries, where SBCE serves as a tool for refining designs and improving product performance to meet changing market demands. Furthermore, the use of relevant technologies such as mathematical modelling, computer software, machine learning, data analytics, and lean principles strengthens SBCE's efficacy by allowing for data-driven decision-making and faster design processes. Despite its widespread use, SBCE has received limited study attention in the previous decade, therefore future research should focus on machine learning integration to improve product development efficiency. The paper analyses SBCE applications across several industries and acknowledges a wide range of industries. The research also emphasizes contemporary studies from 2013 to 2023 to provide current and forward-thinking views. Additionally, the study examines how researchers incorporate SBCE into development processes and its practical engineering applications.

***Keywords*:** *Lean product development, set-based concurrent engineering, set based design, machine learning, computer software.*

1.0 INTRODUCTION

Toyota's Product Development System (TPDS) has enabled the company to manufacture high-quality automobiles quickly, economically, and profitably. In order to achieve this, they must focus on innovation and use Lean Product Development (LPD). Lean is now one of the most often used concepts in efforts to enhance engineering processes. 'Lean' was first defined as a set of Toyota-created principles and ideas in the seminal book 'The Machine that Changed the World'. [1] and [2] define lean is about aiming for excellence through the removal of waste and the incorporation of practises that help reduce costs and improve the overall performance of products, processes, and the organisation. [3] state that Toyota achieves this by delaying decisions, communicating frequently, and creating multiple prototypes. While some aspects of Toyota's development process may seem inefficient, they consistently launch more vehicles each year than other competitors, ensuring a steady stream of new and high-quality products. Study by [4] and [5] regarding on TPDS, the company that created the well-known Lean Manufacturing (LM) system, also created TPDS. TPDS makes use of lean manufacturing (LM) principles and techniques like as value. Other than that, [6] involves in construction study, the use of action-research methodologies is vital, since they enable teams to continuously improve through cycles of planning, doing, reflecting, and learning. By integrating action-research methodologies with lean concepts, construction teams may adapt to the specific obstacles of each project, leading to lasting success through continual improvement. Using stream mapping, 5S, Kanban, and continuous improvement, waste can be eliminated in product development efforts and deliver excellent products to market more quickly than competitors leading opposition. According to [7], because SBCE has so many consequences for organisations, nearly all of the procedures and working techniques will need to be modified. The "Lean Product Development System" recognises it as a highly integrated component of the overall system. Additionally, [8] states LPD contains six strategies: supplier involvement, concurrent engineering, cross-functional teams, activity integration, a heavyweight team structure, and strategic project management. [9] state lean practices are largely concerned with optimising manufacturing and production processes. These practices are intended to reduce waste, shorten lead times, and improve process flow. They may not handle difficulties such as storage, inventorying, and waste management, which are classified as secondary or supporting processes. To properly address these difficulties, lean and green practices must be integrated. This integration entails broadening the scope of lean practices to include environmental responsibility concerns. This could involve for example creating items using eco-friendly materials, lowering the environmental impact of packaging and considering end-of-life disposal in product design.

Through substantial study and intellectual contributions from these authors that have illuminated SBCE's complex aspects, revealing its technical applications and efficacy. The work provides a basis for both researchers and practitioners and creates a comprehensive framework for integrating concurrent processes, boosting technical creativity and efficiency.[10], [11], [12], [13], [14], [15] and [16] mentioned that related to the LPD, SBCE is a well-known approach that explores the design space thoroughly, leading to enhanced innovation by considering a range of alternative solutions and narrowing them down to the optimal solution. [17], [18], [19], [20] define SBCE as where participants in the design process independently and concurrently reason about problems, generate sets of solutions based on new knowledge, and share the findings. They continually narrow sets of solutions as the design progresses, taking into account new data from development, testing, the client, and other participants. Furthermore, [21], [22], [23], [24], [25] explain that SBCE is a method to ensure that client expectations are completely understood and that the design fits the needs of different functions, critical design decisions are purposely delayed until the last feasible moment. Many methods of engineering design are focused on lowering cycle time in accordance with the well-known quote, "Do it right the first time." In terms of design approach, this has frequently translated into a desire to propose the best solution as quickly as feasible. While [26] state that SBCE, also called Set-Based Design (SBD), looks at sets of possible paths to find methods that are likely to work. Instead of picking one good idea and working on it until it works, SBCE or SBD uses these sets to deal with a wide range of tasks. Other than that, in a study by [22], [27], [28], [29], [30], [31], [32] and [33], SBCE is the process of project development by simultaneously refining several designs and discarding just the ones that have been shown not to work for further expansion and development. [29], [34], [35] and [36] state the designers can explore numerous options before committing to one, allowing for more flexibility than with point-based methodologies. A design team can review and integrate design alternatives for each participant, weigh input from multiple participants, and study trade-offs between individual and project values. Additionally, support from [37], there are two main ways to do collaborative design: point-based and set-based. Point-based is when people share exact values of design parameters, and set-based is when people share lists of accepted parameter values. Along with many others, the second method is more promising: using sets instead of exact values lets you cover the whole design space and quickly run through the options, refining them and reducing the requirements over time.

In order to evaluate the current state of SBD and find areas where more study is needed, [38] conducted a literature review of 122 scholarly journal publications and conference papers from 1997 to 2019. In order to complete these objectives, they conducted a systematic literature review to locate and evaluate the most appropriate and influential studies. The research indicates that current best practices in SBD centre on decision analysis, with a growing interest in uncertainty model-based system engineering (MBSE). They discovered that most SBD studies employ quantitative approaches and are concerned with applications involving individual parts or rather simple systems. The majority of the applications we researched involving complex systems were qualitative. The areas of requirements engineering, MBSE, uncertainty modelling, multiresolution modelling, adversarial analysis, and programme management are all areas where they see the need for further SBD study. The author observed that a significant portion of the current research focuses on decision, risk, and trade space analysis, with a growing emphasis on uncertainty modelling and MBSE. Two-thirds of the literature is devoted to quantitative SBD methods. Numerous of these methodologies address basic component or system design issues, whereas methodologies for complex systems are more likely to be qualitative and descriptive. Additionally, approximately 40% of all publications consist of complex system applications.

The purpose of this review paper is to investigate the concept of SBCE which has demonstrated significant potential across different sectors, generating major interest and attention from both industry and academia. Nevertheless, the advancement of SBCE is currently in its early stages since [8] state there appears to be a lack of organized industrial and academic research especially on the application of lean ideas into the PD process in the existing research. Thus, this paper review aims to;

- Research the method applied in SBCE in industrial applications.
- Provide a comprehensive overview of the industrial applications of SBCE in each sector.
- Recommend future SBCE directions.
- Provide some potential solutions to the existing issues.

The subsequent sections of the paper are structured in the following manner. Section 2 provides some background and general concept introduction to the criteria. Section 3 explains how the methodology of this review paper was conducted and Section 4 discusses the analysis of the current state of research on SBCE application. Section 5 provides an overview of the fundamental principles, essential technology, and practical applications of SBCE in various industries. Section 6 presents some observations and recommendations for further work, while Section 7 provides a summary and conclusion.

2.0 BACKGROUND

2.1 Lean Product Development (LPD)

[2], [39] described that LPD is an innovative and efficient method for product design and creation that focuses on increasing customer value while decreasing waste. After 25 years, [40] A study that Lean has had an impact far beyond the realm of business operations, structure, and organisation, into our daily lives. The principles of lean had a tremendous

impact on the management of our healthcare and educational institutions. From its beginnings on the assembly line at the top automotive manufacturers, Lean has progressed a long way. Its influence on 21st-century strategic and operational management thought is undeniable, and it is constantly developing. This methodology, based on lean manufacturing concepts, emphasises continual improvement, collaboration, and flexibility. It emphasises minimising lead times, optimising processes, and encouraging cross-functional communication to improve overall efficiency and innovation. The goal is to develop goods that fulfil the needs of customers while using as few resources as possible, shortening time to market and increasing overall competitiveness. To streamline the entire product development lifecycle, LPD frequently employs approaches such as iterative prototyping, value stream mapping, and cross-functional team cooperation. This is in line with prior research as a study by [41] that show how Industry 4.0 (I4.0) technology can improve product lifecycle management and product development methods. The product development process can be made more agile and dynamic with the help of I4.0 resources. It is very important to understand the concept of lean since [42] state that a lack of a clear understanding of lean and its performance evaluation has led to the failure of lean practice. Most of the performance measures of lean have been developed for the manufacturing or production function of the organization.

Using design rules is the best way to support the integrated design process that takes into account both service and product features. Thus, both the company's internal limits and client needs can be met from the very beginning of the design process. state that LPD practises may also improve innovation management and the development process's capacity to maintain a customer focus, which in turn affects how innovation projects are managed. Summarize from [43], LPD follows 13 principles. The 13 principles of Lean Product Development (LPD) focus on delivering customer value, exploring ideas early, maintaining balanced processes, standardising practices, and ensuring seamless integration across teams and suppliers. Key elements include strong leadership, engineering expertise, continuous improvement, visual communication, and aligning technology with people.

Importantly, LPD should be seen as a unified system—not isolated methods. Inspired by the Toyota Product Development System (TPDS), LPD integrates process, tools, and skilled people. When applied together, these elements enhance product development and foster a culture of growth and innovation. Additionally, the concurrent engineering system’s influence can be observed in the emerging body of work known as the Lean NPD subset of this technical literature, which has emerged more recently. This is demonstrated by [44] through the implementation of the SBCE method. Advocates assert that SBCE, combined with knowledge management and delayed decision-making, is a key element of Toyota’s new product development system and is as effective and distinctive as the Toyota Production System.

Other than that, according to [45], Indian manufacturers struggle to launch new products due to costly inefficiencies. Adopting a new LPD framework can help reduce waste and achieve their goals. Furthermore, [46] a study illustrated the utility of the framework in agroindustries, as shown by the fruit processing company's adoption. The framework can enhance product development using the Lean methodology, thereby improving the economic benefits and environmental impact of fruit processing companies throughout the product life cycle. Initially, the LPD framework was flexible to the project type. Companies developing products can use SBCE to produce many items simultaneously, reducing rework. The proposed framework can be utilised in numerous industrial areas to promote a sustainable product life cycle. Related to sustainability, [47] incorporates concepts from an introduction to sustainability methods into SBCE and LPD, with a focus on establishing needs and motivations for design from a sustainable perspective. The focus of this updated declaration is on ensuring that SBCE and LPD techniques are sustainable from start to finish, bringing them in line with the larger goal of global socio-ecological sustainability. As a result of incorporating sustainability into these design and development methods, environmental and social considerations will always be at the core of the product creation process. Futhermore, [48] state that frontloading (e.g., utilising SBCE) in NPD reduces total cost by more than half and improves lead time by 20%, resulting in a corresponding delay loss when loading resources later in the process. This may result in missed market opportunities.

2.2 Set-Based Concurrent Engineering (SBCE)

Toyota uses SBCE in its product development system, which sets it apart from other manufacturers. [49] mentioned the three principles upon which SBCE relies are the following: (1) Map the design space;(2) Integrate the design space through intersections; and (3) Establish feasibility before commitment. All of these guidelines rely on a precise representation of the design's diversity. [50] initially, Toyota can choose from among all of the various design alternatives, and then, through a process of gradual elimination, they reduce options to a single design. [51] describe how design participants use SBCE to develop and communicate about solutions simultaneously and independently. The design process involves narrowing down solutions based on development, testing, simulation, trade-offs, customer, and other information until a consensus is reached. [52] and [53] define set-based design as a method that evaluates and contrasts potential solutions to design problems by considering several possible configurations of "SETS" of design parameters and reasoning through each one. The goal of set-based design is to gather specific knowledge and reduce inaccuracy to a point before committing to a specific design. Furthermore, [54] state that knowledge capitalization is an integrated approach for maintaining, sharing, and reusing the body of information gleaned from design initiatives.

A study by [55] in the automotive industry, the exchange of rich sets of solutions (relative to single point solutions) has been shown to increase the diversity of options available for achieving agreement with partners and thus reducing costly iterations. [56] mention set-based approaches differ from optimization-based approaches in that point solutions are traded iteratively and automatically, guided by one or more optimization methods. All designs should strive for optimization which is to maximise gain while minimising expense under the constraints imposed by physical limitations. Apart from that, which is defined by [57] defined SBCE is used to demonstrate the disadvantage of design rework. [58] illustrate in Figure 1(b) that the SBCE is thinking about more than one option at a time, in contrast to the PBCE. The SBCE goes on to iterate on numerous possibilities simultaneously, using an effective decision-making process to eliminate ideas that are not conclusive until it finds the optimal one. In order to speed up project development and eliminate infeasible solutions, it centres on bringing together a set of design options through the use of various tools and methodologies.

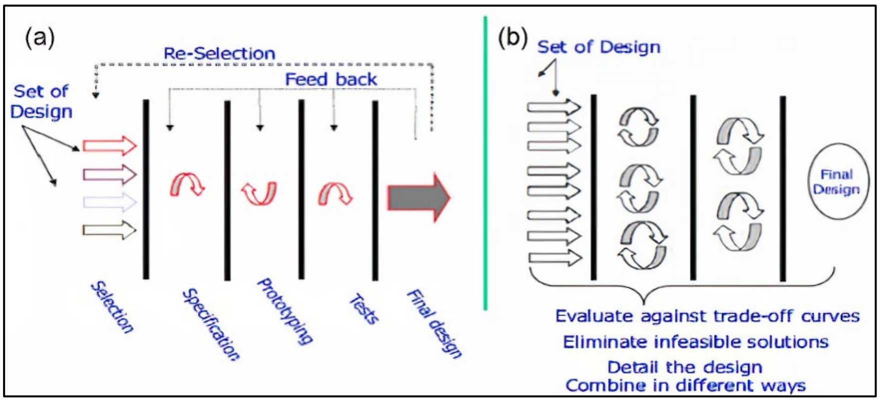

Figure 1: Differences between (a) PBCE and (b) SBCE process. [58]

According to [59], the output of SBCE implementation on the business case is predicated on the possible concrete advantages in four main areas: 1) enhanced product innovation, 2) enhanced product performance, 3) reduced material cost effect, and 4) increased project success likelihood. We have seen a rise in the level of innovation and knowledge creation: Using the SBCE process model, 144 different configurations of the system were found in the case study. This may provide a chance for Jaguar Land Rover (JLR) engineers and designers to experiment with other ideas inside the design space, free from the constraints of the company's present methods of product development. To achieve the best result by implementing the SBCE method, [21] stated that it is essential to gather and comprehend client needs before initiating product development. The chief programme engineer (CPE) might assemble a cross-functional team of marketing and technical experts to collect and study these in depth. Since [60] described the Chief Engineer also acts as the customer's representative and heads the design team as a whole. As a result, the team will be able to communicate better and tackle the first area for development. Also, [61] state about the strong thing about SBCE is that it can look at unclear and unfinished models for new parts of the system. This cuts down on the number of possible designs before they are fully developed.

[62] and [63] described robust design is an alternative development and the reduction and resolution of uncertainty are two important ideas in the field of SBCE. Remarkably, th majority of SBD methods stress the significance of these fundamental principles. During the early stages of product development, robust alternative development ensures that all viable options for the product's design are considered before a final decision is made. Concurrently, a systematic strategy for addressing uncertainties, including risk analysis, prototyping, simulations, and testing to base decisions on facts rather than assumptions, is essential for the reduction and resolution of ambiguity. While some have attempted to optimise product design with concurrent engineering (CE) by [64], others have focused on optimising the manufacturing process of an entire factory plant. Virtual Machines (VMs) prove to be highly advantageous during the conceptual product design, development, and evaluation of various solutions for consistent technological processes. This is particularly true when concurrent engineering is being implemented. Due to the fact that modifications are implemented on virtual models of the process, it is possible to verify all design alternatives and identify all potential errors and defects on time at the lowest possible cost. It's important to note that some SBD practices may have a propensity to focus exclusively on specific components or procedures, even while this attention is crucial for increasing the efficiency and quality of product development processes. A narrower SBD strategy may be sacrificed in favour of more specialised methods such as value stream mapping, Analytical Hierarchy Process (AHP), textual modelling, and machine learning.

3.0 RESEARCH METHODOLOGY

Following the recommendations of [65] and [66] this work utilized a systematic literature review approach. [67] provides a summary of the research adopted as illustrated in Figure 2. As previously stated, the purpose of this work was to analyze the method that is applied in SBCE in industrial applications; provide a full review of the industrial uses of SBCE in each relevant stage and make recommendations on the future directions of SBCE as well as offering some possible answers to the problems that currently exist to have clear research gap for further study. The evaluation began with a scoping process, during which several key articles on the application and assessment of SBCE were reviewed. This method was useful for figuring out what details were needed from the source studies and for generating a list of possible search terms. The terms "lean product development," "set based concurrent engineering," "set based design," "artificial intelligence," and "machine learning" were included in the search phrases since they are linked to the application of SBCE.

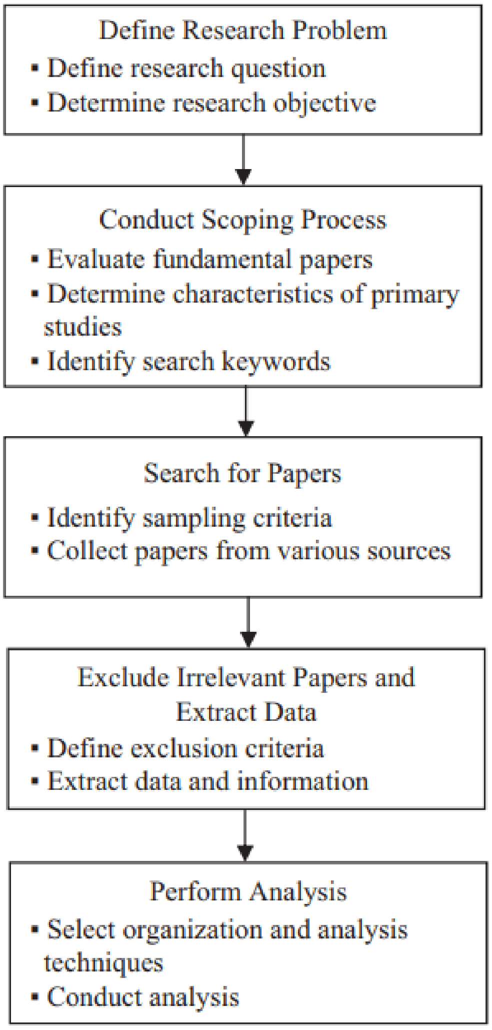

Figure 2: Methodology for review paper [67].

In general, the approach consisted of searching all fields rather than searching in a particular portion, such as the title, the abstract, or other similar sections. The research articles that were the primary focus of the search were those that were written in English and were published in a variety of online databases including Emerald, IEEE Xplore, Science Direct, Springer, Sage, Taylor and Francis, Wiley, and Scopus. The most relevant journals and conferences included the Procedia CIRP, Int. J. Internet Manufacturing and Services, International Journal of Advanced Computer Science and Application, Concurrent Engineering Research and Applications, Systems Engineering, International Journal for Numerical Methods in Engineering, International Journal of Lean Six Sigma, Proceedings of the International Conference on Engineering Design (ICED), Procedia Engineering, Decision Support Systems, Computers & Chemical Computers and Chemical Engineering, Materials and Design, Journal of cleaner production, Advances in Transdisciplinary Engineering, Processes MDPI, International Journal of Computer Integrated Manufacturing, Expert Systems with Applications, Requirement Engineering software, Materials Science Forum, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Journal of Mechanical Engineering and International, Journal of Advanced

Manufacturing Technology, Journal of manufacturing technology and management and Al-Khawarizmi engineering journal.

3.1 Classification Criteria

Based on Table 1, this is the primary research for the SBCE study sorts through the extensive amount of literature by focusing on the different phases that researchers go through to achieve the goal of implementing SBCE. SBCE is analysed in the literature, which provides a precise description, an in-depth understanding of its fundamental concepts and principles and an extensive investigation of its possibilities.

Table 2: Attribute and criteria of the paper.

Attribute	Classification Characteristic
Content of literature	Ideology - Definition of SBCE, understanding the concept/principle and SBCE potential Framework - General descriptions of SBCE, analysis of the method and detailed case study. Application - Description using the SBCE principle in various fields and a detailed specification.
Level of integration	The conventional method is more effective compared to the traditional method - Enabling technological input in the line model. - Computer software system for input during development. - Combination of mathematical modelling. - Machine learning method
Type of publication	- Journal paper - Book chapter - Conference paper - Thesis

By presenting both overviews and in-depth analyses of SBCE, along with a detailed case study illustrating its methods, it offers a solid framework. Furthermore, the literature exhibits the SBCE principle's application across a variety of fields by providing detailed specifications to illustrate its practical implementation. The effectiveness of the conventional method is significantly enhanced by the integration of enabling technological inputs resulting in a higher level of integration compared to traditional approaches. As evidence of the study's wide-ranging influence and contribution, the results were published in a variety of formats, including journal articles, book chapters, conference papers, and thesis. The number of findings for SBCE applications across various databases is shown in Table 2. SBCE models are used in engineering and design for interdisciplinary teamwork and seamless integration in the creation of complex systems. This encompasses all branches of engineering, such as mechanical, electrical, software and construction. There may have been advancements in the form, content, and application of SBCE models over time.

Table 2: Amount search for SBCE application in different databases.

Time	Google Scholar	Web of Science (Topic)	Scopus (Topic)
2013	96	2	5
2014	93	0	5
2015	107	1	1

2016	123	3	1
2017	110	2	4
2018	145	1	3
2019	117	3	5
2020	105	1	5
2021	91	1	1
2022	88	1	1
2023	50	1	1

3.3 Literature Review Approach

This review is based on scientific articles that have been examined by other researchers in the field, as well as certain technical reports or whitepapers written by those researchers. The review concentrates its attention primarily on SBCE ideas, important technology, and practical applications in industry.

A thorough analysis of the literature on SBCE was conducted, following a systematic process consisting of four steps: (a) conducting searches in various databases using appropriate keywords; (b) excluding irrelevant research papers by reviewing abstracts; (c) carefully examining the full texts of relevant papers and organizing them based on the criteria described in subsection 3.0 and (d) conducting a comprehensive evaluation that took into account various characteristics of the literature, including the stages of the lifecycle, themes of the content, publication timelines, and the development of concepts, technologies, and methodologies over time as illustrated in Table 3.

Table 3: Review of the literature in the study field.

Search Area	Content
Database platform	Science Direct, Scopus, Web of Science and Google Scholar.
Search keyword	Set based concurrent engineering application, set based design application, lean product development.
Time (Year)	2013-2023

From 2013 to 2023, the data shows a fluctuating pattern in research publication output related to the number of papers for SBCE that are related to technology and application as shown in Figure 3, with a clear emphasis on technological advancements and practical applications. Not a single technological paper was published in 2013, 2014, 2019 or 2021, indicating a gap or a change in research focus during those years. On the other hand, a slight but noticeable increase in the number of papers devoted to technological topics may be seen in 2015, 2016, 2017, 2018 and again in 2022 and 2023. There were two technical papers with two application papers published in 2015. Only one technological paper in 2016, but there were four application papers. Two application papers accompany a single technological article in 2017. The output of application-oriented publications is more stable, with peaks in 2016, 2020, and 2022, as shown by a parallel analysis. The year 2016 saw the publication of four application articles, indicating a noteworthy shift in emphasis towards real-world applications. In 2020, four publications contributed to this area, possibly showing a rise in practical importance, and this time stands out as one in which the emphasis is most heavily placed on applications. This analysis highlights the ever-changing character of research interests, suggesting possible transformations in the technical landscape and the increasing importance of application-oriented studies over the time period under consideration.

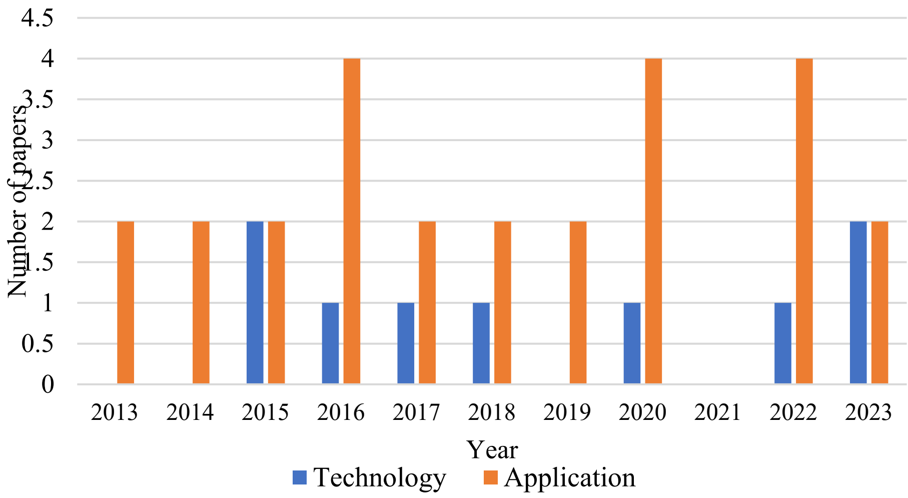

Figure 3: Number of papers of SBCE related to technology and application.

Initially, 1173 articles were gathered from the identified sources, as shown in Figure 4, implementing the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) diagram, including 1125 from Google Scholar, 16 from Web of Science, and 32 from Scopus. After removing 23 duplicate records, the total was reduced to 1152. A careful review of the titles and abstracts led to the exclusion of 889 articles that were not relevant to the study, narrowing to 94 papers. After a thorough full-text assessment, the selection was refined further, resulting in 48 articles that were directly relevant to the application of SBCE.

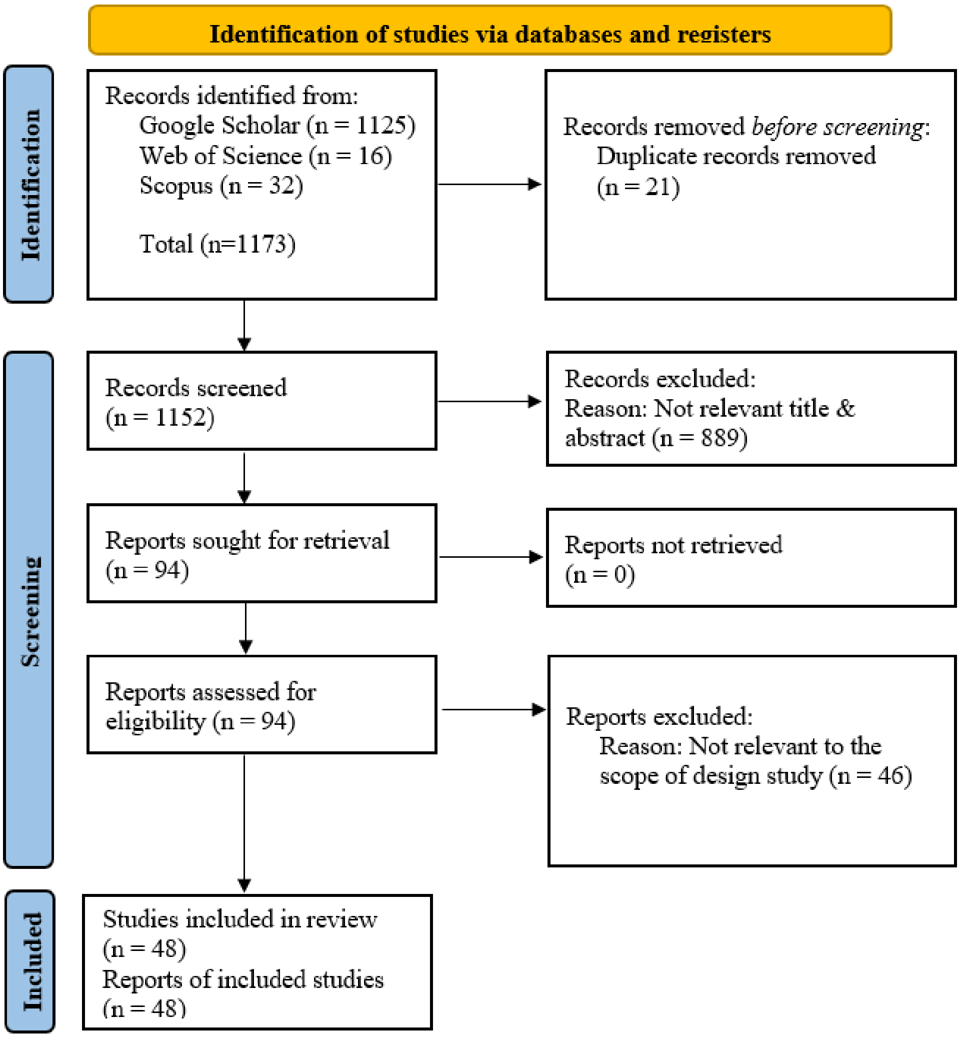

Figure 4: PRISMA flow diagram for literature review related to SBCE application.

The articles were then reviewed and filed according to the applicability to specific sectors, such as the "automotive industries," "aerospace industries," "construction industries," "general manufacturing," and others. At first, only items that were loosely related to SBCE application were considered rejected. This was accomplished by reviewing and criticizing the articles' abstracts and titles. The restriction of a certain time period 2013-2023 was also applied to several documents and papers in order to eliminate them from consideration. On the other hand, the majority of the documents that were not included in the review were mentioned in the paper's introduction and/or background sections in order to construct a conceptual foundation for the review.

By looking at study topics from 2013 to 2023 in Figure 5, show how the methods used in the field have changed and evolved related to the application method in SBCE. In particular, the "step by step" concept is consistently emphasized in the early years, 2013 and 2014, with two articles each dedicated to this method. However, studies exploring areas like mathematical modelling, software, and machine learning are notably lacking throughout this time frame. A small but significant change occurred in 2015 with the publication of a single work devoted to mathematical modelling. Increased use of the "step by step" method, with as many as three papers based on it by 2016, and ongoing mathematical modelling can be seen in later years. However, there is a paucity of writing on the subjects of software and machine learning. The year 2019 marks a major milestone, with one publication dedicated to machine learning, showing a growing interest in this subject. In 2020, there will be fewer "step-by-step" books, but more papers on software. In 2022, the "step by step" method reappeared, this time with a study on software to back it up. Three studies published in 2023, the final year of the study, show an increased focus on machine learning and other cutting-edge computational approaches. This analysis highlights the ever-changing nature of research goals by illuminating shifts in research methodology and an increasing leaning towards the use of machine learning in subsequent years.

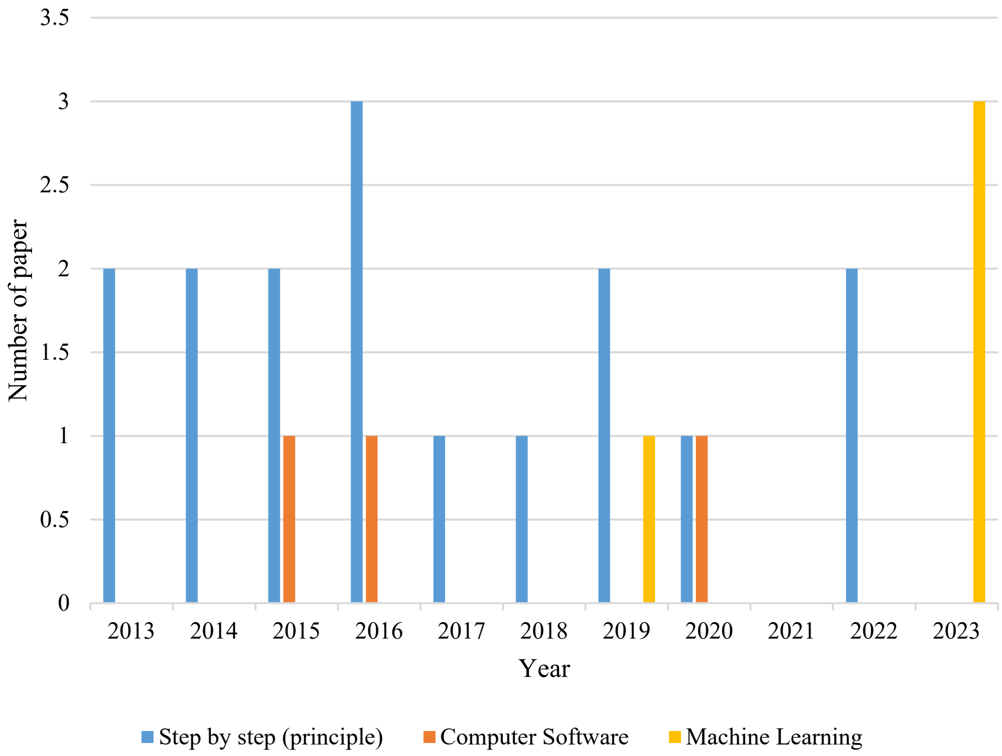

Figure 5: Number of papers related to the level of integration in the SBCE application method.

4.0 ANALYSIS OF THE SBCE RESEARCH.

The information illustrated in Figure 6 is that studies and papers of industries involved in SBCE application were published in different fields from 2013 to 2023. From 2013 to 2023, the "Mechanical" industry had a strong presence, with a rating of 16, while other sectors like "Construction," "Electrical," "Telecommunication," "Medical," "Chemical," and "Food" had little or no presence, with most ratings of 0 or 1. This means that most research and writing during this period was focused on the "Mechanical" industry.

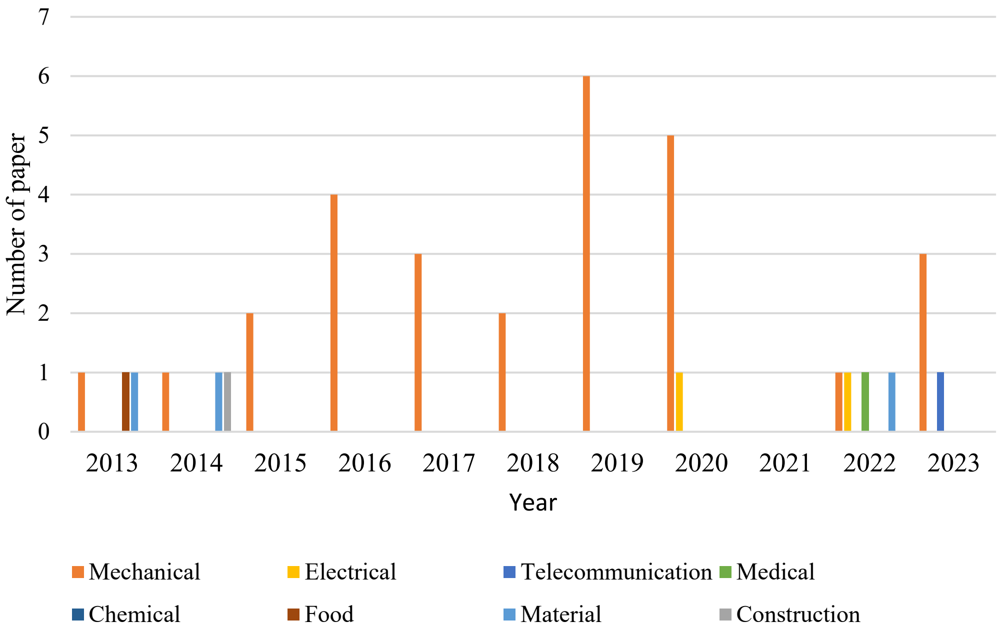

Figure 6: Number of paper of industries involve in SBCE application.

The analysis of research output from 2013 to 2023 as shown in Figure 6 reveals varied attention to various engineering fields. Mechanical engineering was the major focus in previous years, particularly from 2013 to 2016, with a rising number of publications dedicated to this discipline, culminating at four in 2016. There has been one paper for food industries and material engineering in 2013 and also one paper for construction. There has a distinct lack of publications in other engineering domains such as electrical, telecommunications, medical, chemical, and food engineering throughout this period. With six papers, the year 2019 stands out as an important time in mechanical engineering research. It is worth noting, however, that there has been little research into other engineering specialties. In 2020, the trend began to reverse, with a decline in mechanical engineering articles and the entrance of electrical engineering research (one paper). The next years, 2022 and 2023, show a broadening of research areas, with contributions in electrical, telecommunications, and medical engineering, showing a greater investigation of technical domains. Interestingly, the years 2021 and 2022 saw a significant reduction in mechanical engineering articles, indicating a shift away from mechanical engineering supremacy. Instead, over these years, there has been a slight increase in electrical and medical engineering publications. The overall trend indicates a shift away from a singular concentration on mechanical engineering and towards a more diverse research landscape, which may represent growing research interests and developing objectives within the engineering field.

4.1 Analysis of Sector Related to Each Field for SBCE Application

Table 4 provides a scholarly resource that neatly organizes several areas of study and the businesses that serve for the SBCE application. Mechanical engineering, chemical processes, building, electric and electronic sectors, the food sector, and so on are all represented in separate rows of this tabular display. The columns that follow explain how these academic fields are embedded throughout various industries. This table's organization makes it possible to investigate the connections between different fields of study and how they overlap and complement one another in practice, highlighting the broad implications of these fields in today's academic and industrial landscape.

Table 4: Sector related in field of study.

No.	Author	Field of study	Sector
1	[68]	Construction	Bridge design
2	[8]	Electric and electronic	Access control system
3	[8]	Electric and electronic	Power transformer
4	[7]	Electronic, graphic industry, automotive and heavy truck	Electronic (traffic monitoring) graphic (paper mills) automotive (design capability) heavy truck (engine)
5	[69]	Food industry	Water cup
6	[70]	Material engineering	Helmet design
7	[71]	Material engineering	Product development
8	[72]	Material engineering	Multilayer porous material
9	[73]	Mechanical engineering	General
10	[27]	Mechanical engineering	General
11	[74]	Mechanical engineering	Ship hull design
12	[25]	Mechanical engineering	Hybrid electric aircraft
13	[75]	Mechanical engineering	Prototype design
14	[76]	Mechanical engineering	Lithium battery
15	[77]	Mechanical engineering	Jet engine
16	[78]	Mechanical engineering	Aerospace engine fan diameter
17	[79]	Mechanical engineering	Aerial vehicle
18	[80]	Mechanical engineering	Surface jet pump
19	[38]	Mechanical engineering	General
20	[81]	Mechanical engineering	Aircraft Vent System
21	[82]	Mechanical engineering	Ship design
22	[83]	Mechanical engineering	Vehicle general design
23	[84]	Mechanical engineering	Aircraft engine
24	[85]	Mechanical engineering	General
25	[86]	Mechanical engineering	Compressor
26	[87]	Mechanical engineering	Automotive metal forming
27	[88]	Mechanical engineering	Management development
28	[30]	Mechanical engineering	General
29	[89]	Mechanical engineering	General
30	[58]	Mechanical engineering	Meta Product
31	[90]	Mechanical engineering	Ship hydrofoil
32	[11]	Mechanical engineering	Surface jet pump
33	[91]	Mechanical engineering	Car roof structure
34	[92]	Mechanical engineering	General
35	[93]	Mechanical engineering	Mechanical transmission
36	[94]	Mechanical engineering	Car seat development
37	[95]	Mechanical engineering	General
38	[96]	Mechanical engineering	Chassis frame truck

39	[97]	Mechanical engineering	Injection molding cooling system
40	[98]	Mechanical engineering	Wind tunnel
41	[99]	Mechanical engineering	Helicopter engine
42	[72]	Mechanical engineering	Swing arm
43	[100]	Mechanical engineering	General
44	[101]	Mechanical engineering	Gearbox design
45	[102]	Mechanical engineering	General
46	[103]	Medical	Medical device
47	[26]	R&D cigarettes industry	Cigarettes
48	[104]	Telecommunication	Product evolution

This extensive collection of papers illustrates the diversity of the discipline of Mechanical Engineering in SBCE Applications, with each publication contributing to a variety of specialized and general areas of mechanical engineering research. [21] and [38] investigate the fundamental principles, concepts, and applications of general mechanical engineering across a broad spectrum. [100] adopt a more specific approach by delving into the complexities of general design, thereby offering valuable insights into the creative and analytical aspects of mechanical engineering.

In the domain of specialized subdisciplines, [10] and [80] focus the research on surface jet pumps, providing in-depth knowledge about this crucial component utilized in fluid transport in the oil and gas sector. Further narrowing the scope, [77] focused on aircraft engines and the cutting-edge technologies and innovations associated with them. [105] deviates from the realm of helicopter engines, investigating the complexities and developments of this particular propulsion system.

[91] dissects the design of automobile roof structures in great detail, focusing on safety, aerodynamics, and structural integrity. [96] construct vehicle chassis frames with consideration for load-bearing capacity and durability. [93] disentangle the complexities of mechanical gearbox systems by concentrating on the design, performance, and optimization of these vital components.

[94] examine the complex field of automobile seat design, focusing on comfort, safety, and ergonomics. [88] present a novel intersection of mechanical engineering and management development, providing insights into the field's business aspects. [97] optimize manufacturing processes by focusing on the precision of injection molding cooling systems.

[98] demonstrate the significance of wind tunnels in aerodynamics research within the field of mechanical engineering through the knowledge of wind tunnels. [106] and [101] examine the specific domains of swing arm technology and transmission design, providing essential insights into the design and operation of these mechanical components. This assortment of papers demonstrates not only the multidisciplinary nature of mechanical engineering but also the scope and depth of research within this dynamic field and its subdisciplines.

5.0 CONCEPT, TECHNOLOGIES AND INDUSTRIAL APPLICATION

To have a complete view of the integration of SBCE through the year in literature, Table 5 provides some information regarding related technologies from 2013 to 2023. Computer software solutions enable collaborative writing and content management in SBCE applications in literature, allowing numerous authors to work on various parts of a project. Authors can explore multiple narrative possibilities and develop them through iterative design procedures using mathematical modelling to create intricate stories and character connections. However, during the period from 2013 to 2023, there was no study related to mathematical modelling. Machine learning algorithms analyze massive literary datasets to reveal writing styles, trends, and reader preferences, helping authors make data-driven narrative development decisions in SBCE.

Table 5: Technologies used in literature.

No.	References	Time	Industry	Integration Method	Related Technologies
1	[72]	2013	Material Engineering	Computer software	Biot Model
2	[68]	2014	Construction	Computer software	2D FEM Calculation
3	[97]	2015	Mechanical Engineering	Computer software	Computer Aided Synthesis (CAS)
4	[96]	2015	Mechanical Engineering	Computer software	2D FEM Calculation
5	[94]	2016	Mechanical Engineering	Computer software	SimaPRO
6	[83]	2019	Mechanical Engineering	Machine Learning	Multi Attribute Tradespace Exploration (MATE)
7	[86]	2019	Mechanical (Mechatronic)	Machine Learning	System Modelling Language (SysML)
8	[107]	2020	Mechanical (Oil and gas)	Computer software	Web based software
9	[108]	2023	Mechanical Engineering	Machine Learning	Bayesian Active Learning (BAL)
10	[74]	2023	Mechanical Engineering (Ship)	Machine Learning	Self-Organizing Maps (SOM)
11	[27]	2023	Mechanical Engineering	Machine Learning	Multi agent system (MAS) [Point set organized research team (PSORT)]

5.1 Related Technologies to Computer Software

The work presents a Probabilistic Set Design (PSD) conducted by [72], method for early design to address uncertainties. The PSD technique allows designers to express choices for a variety of solutions and performance criteria under uncertainty using flexibility, robustness, and preference. It is used to build a multilayer sound absorption or insulator material and develop a performance prediction system using set-to-set space mapping and space narrowing. The method's integration with the Biot model calculating system shows its versatility. The PSD calculating system, a Microsoft Excel add-on, that designers to enter design factors and performance parameters and provides results. This approach may be scalable across design fields, addressing uncertainty in multi-objective product development.

The study conducted by [94] Life cycle assessment (LCA) and sustainability analysis are best performed with the help of SimaPRO, a powerful and flexible piece of computer software. Throughout a product's or process's whole life cycle, it is essential to help organizations, researchers and professionals evaluate the product's or process's environmental, social and economic implications.

Other than that, [97] conducted a study on the algorithmic development of designs is what computer-aided synthesis (CAS) is all about the synthesis phase of the design process. The goal is to leverage the power and efficiency of modern computing to reduce repetitive tasks for designers and accelerate the exploration of potential solutions, helping identify the optimal solution quickly without having double job.

Furthermore, [96] implement the 2D Finite Element Method (FEM) in his study since it is a powerful method that uses numerical techniques to tackle complex engineering and scientific problems. As a crucial tool in modern simulations, it allows engineers to evaluate and refine designs while gaining deeper insights into how systems function.

While [107] integrate the K-shelf idea for facilitating SBCE applications and show how it can be done through a piece of web-based software. A surface jet pump (SJP) case study from the industry is used to verify the results. K-shelf's capacity to record design justifications and keep them organized, as well as its ability to facilitate comparisons across groups of design alternatives make it an invaluable tool.

5.2 Related Technologies to Mathematical Modelling

In the period from 2013 to 2023, there is no technological relationship between mathematical modelling and SBCE application. However, there are some studies by [100], which implements mathematical modelling in his design development concept. Fuzzy decision-making helps designers evaluate designs early in product development, even when information is limited and judgments are uncertain. Using fuzzy terms like 'good,' 'fair,' or 'bad', designers can better assess the feasibility, reliability, and quality of different options, making the early design process clearer and more reliable.

While [101] offer a Design Information Solid (DIS) paradigm, which smoothly integrates geometric and non-geometric design information into CAD geometry. DIS stores design details directly within the CAD model as attribute data, unlike other methods that rely on separate databases. It captures both geometric and design-related information such as materials, part relationships, and design intent. Designers can use preference numbers (PNs) and preference graphs (PGs) to express their choices clearly, whether for continuous or discrete options. This makes the data more complete and easier to understand. DIS supports concurrent engineering by organizing and managing various types of data within CAD. The authors also introduce a hybrid model called Preference Set-Based Design (PSD), which uses PNs to handle design uncertainty. A case study on a shaft and multispeed gearbox shows how this approach can speed up the design process and offer more design possibilities.

[106] research shows how 3D-CAD and CAE may be used together to create a swing arm. Ultimately, it seeks to efficiently realize designer-intended multi-objective satisfaction. Using PN to reflect designer preferences and a set propagation method to calculate possible performance spaces, the system resolves uncertainty in early design phases. It reduces design space by coordinating tools to streamline the modification of CAD models and FEM analysis. The system can effectively produce a variety of design solutions and record the preference structures of designers. Users can then pick the best possible solution by picking the values that best fit based on the requirement. This method simplifies the design process while simultaneously guaranteeing its durability and the happiness of its creators.

5.3 Related Technologies to Machine Learning

Using the System Modelling Language (SysML), which implements the Python language, [86] Conduct research on mechatronic electrical compressors to determine a feasible solution for electrical compressors that maximizes all potential trade-offs, including reliability, cost, manufacturability, and durability, thereby identifying the optimal option. The utilization of SysML facilitates graphical representation of the composition, functionality, and interconnections of systems, rendering it an essential tool for engineers and architects engaged in the development, evaluation, and documentation of intricate systems.

[108] utilizing Bayesian Active Learning (BAL), the automation of these processes becomes feasible as BAL can dynamically create supplementary query data points, enabling the emulator to meet the specified criteria effectively. A unique function is developed and maximized based on BAL in order to produce additional designs for the determination of feasible regions.

[74] propose a multi-stage space reduction technique that integrates the features and benefits of a Self-Organizing Map (SOM) and the rough set theory. The process of knowledge discovery and data mining was performed on a set of simulated data samples. The acquired knowledge from this analysis was then utilized to inform the optimization of the design and identify a specific subspace that merits attention. This targeted subspace has the potential to enhance the efficiency of the optimization process.

The Point set organized research team (PSORT) methodology study by [27] employs concurrent engineering principles by decomposing a project into smaller subproblems and allocating an agent to generate a design set for each subproblem. Consequently, increasing the number of subproblems in a project necessitates a proportional increase in the number of agents and design sets required to successfully address the project. The subproblems and the designs in this study represent separate parts.

6.0 DISCUSSION BASED ON OBSERVATION

SBCE relies heavily on observation and advice to improve efficiency. Organizations can learn where they might enhance performance by closely monitoring the processes and results of concurrent engineering efforts. Using these findings, the SBCE method can be fine-tuned to meet the requirements of a given project. The recommendations derived from these findings provide significant direction for future projects, facilitating better decisions, more efficient processes, and better outcomes from concurrent engineering efforts. [109] mention that a company needs to have well-defined procedures for tracking what constitutes good and bad design across projects. Toyota, for instance, employs checklists that detail the company's accumulated expertise. The checklists provide thorough information on "good and bad design practices, critical design interfaces, manufacturing requirements, and performance requirements" and walk designers through each step of the design process. guidelines that reduce design to a joke"

Table 5 shows that SBCE has been increasingly popular in the realm of mechanical engineering. Utilizing tools like mathematical modelling, computer software, and machine learning, the table provides useful insights into the integration methods utilized in SBCE. These results further demonstrate the close compatibility between SBCE and the field of mechanical engineering, where optimization of product development processes is typically achieved through the use of mathematical modelling, CAD software and machine learning techniques. The mechanical engineering industry's dedication to progress in product design and production is shown in the widespread adoption of these SBCE technologies.

According to the statistics, research on machine learning in the field of SBCE is still very limited and there is no clear upward trend in the activity level of its researchers. This would indicate that machine learning has not yet achieved a significant amount of momentum as an integration tool within contemporary engineering practices.

6.1 Recommendation for Future Work Related to Technologies

Developing robust methods for evaluating and managing risks in concurrent engineering projects remains a crucial area for future research within the SBCE framework, as it will lead to more reliable outcomes. Additionally, expanding the application of SBCE to areas such as sustainability and multidisciplinary research presents significant opportunities to drive innovation. [94] propose additional investigation into tool automation and integration with other Product Development Process (PDP) frameworks and tools is warranted especially in the context of sustainability. It is suggested that a case study be conducted to evaluate the advantages of varying degrees of sustainability. Decisions influenced by sustainability concerns should be made early in the development process, and a cost-benefit analysis should be performed to compare this strategy with the current one.

Other than that, [97] recommend that CAS can speed up the design development process by significantly giving designers more control over how they use knowledge and helping them come up with different design solutions. This method is consistent with Lean Design concepts and can aid in efficient decision-making by refining requirements, accepting varied stakeholder opinions, or negotiating using performance metrics. Furthermore, the capacity to store and operationalize expert knowledge guarantees that key insights are retained for future usage, hence improving knowledge maintainability in the organization's design processes.

[100] The study concerns the realm of concurrent engineering; it is crucial to pay attention to constant development and modification. First, artificial intelligence (AI), machine learning (ML), and augmented reality (AR) should all be investigated for their potential to improve real-time decision assistance and simulations. More people should be able to use it, hence user-friendly interfaces should be built. To stay up with changing design needs and best practices, the decision support system must undergo regular updates and modifications.

Other than that, as stated by [86], more informed choices and superior product designs can emerge from such a collaborative effort. The implementation of SBCE and MBSE can also be simplified through R&D to make the methodologies more widely applicable and flexible across a wide range of sectors and product types. To reduce cycle time on design and development, it is also worth looking into ways to improve and optimize algorithms and decision-making processes inside SBCE.

Furthermore, [108] highlight the importance of recent research on multifidly modelling employing multiple data sources, showing its potential utility in industrial applications. As a result, they advocate broadening set-based analytical target cascading (SBATC) to include more data sources, ensuring its usability and usefulness in a wider range of circumstances. These future efforts aim to improve the SBATC method's versatility and applicability in handling hierarchical design optimization challenges.

Lastly, [27] recommend to investigate how SBCE interacts with various design team compositions to enable numerous agents to work on a single subproblem. Explore SBCE in different team structures. This might offer some fresh ideas for SBCE coordination techniques. Use a variety of problem-solving techniques: During iteration, experiment with alternative solving techniques to obtain insights and explicitly model elements like uncertainty. This may result in more effective SBCE approaches.

7.0 CONCLUSION

In conclusion, the evaluation reveals several significant challenges to the adoption and implementation of SBCE. These include the method's inherent complexity, high resource demands, dependence on human expertise, time-consuming processes and labor-intensive evaluations. Furthermore, the findings suggest that gaps in knowledge and resources pose a barrier rather than mere shortages, emphasizing the critical need for both to support effective SBCE practices.

As part of the teamwork, members use a variety of approaches to identify problems and develop solutions. These techniques make teamwork more difficult and more rewarding while also facilitating better and faster resolution of common project problems. These results show potential areas where SBCE could be strengthened and fine-tuned in the future. [111] claim the LPD literature asserts that the implementation of set-based engineering is a beneficial strategy. This approach involves allocating time and resources during the initial stages of product development, which effectively minimizes uncertainty and subsequently reduces the necessity for iterations in subsequent development phases.

The growing popularity of SBCE in mechanical engineering is further widespread adoption of associated technologies. SBCE techniques are consistent with the goal of efficient product development in mechanical engineering since they make use of mathematical modelling, computer software, and machine learning. However, the limited research activity in machine learning within SBCE suggests that there is room for further exploration and development in harnessing machine learning as an integration tool in contemporary engineering practices. To apply machine learning effectively in SBCE, researchers need access to large, high-quality datasets that reflect different stages of the product development process. Unfortunately, these kinds of datasets are rarely available. Much of the relevant data is tied to industrial projects that are confidentiality agreements, making it difficult to share or publish. Even when data is accessible, it is often inconsistent or collected in formats that vary from one organization to another, which complicates its use for training or validating machine learning models. Without reliable and standardized data, it becomes challenging to fully explore or demonstrate the value of machine learning in the SBCE context. As a result, throughout the 2013 to 2023 period, research in this area remained limited, not because of a lack of interest but because the foundational data infrastructure simply was not in place. Finally, this analysis clarifies the current state of SBCE research and its future directions, providing useful information for concurrent engineering and related topics.

DECLARATION OF CONFLICTING INTERESTS

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ACKNOWLEDGEMENT

This research was funded under UTM Encouragement Research Grant.

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