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REVIEW PAPER

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System design and engineering trade-off analytics: State of the published practice

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Abstract

System design and engineering involves making decisions involving multiple stakeholders with diverse and, potentially conflicting, objectives. As more and more data become available with digital engineering, big data, and data science, trade-off analytics will be an increasing important tool for engineers. We used a structured literature survey with Web of Science key words and bibliographic, categorical, and bibliometric analysis to answer 14 research questions. As our literature survey demonstrates, trade-off analysis can be found in almost every engineering domain. We provide several insights from the literature survey for educators and practitioners.

KEYWORDS
SEE11 decision analysis, management, SEE26 modeling and simulation

1 | INTRODUCTION

Systems are developed to create value for stakeholders by providing desired capabilities. Stakeholders include investors, government agencies, customers, acquirers, system operators, system developers, trainers, and system maintainers, among others. Decisions occur throughout the system life cycle, and system decision makers (DMs) make important system design decisions during concept definition, system definition, system design, deployment, operation, and disposal.

The systems decision process[1] has multiple stakeholders with competing objectives. With limited resources, to achieve one objective at a desired level typically requires trade-offs between the levels of other objectives. Usually, the more complex the system and the more stakeholders involved; the more analysis is required to achieve the best balance between objectives. The process that leads the determination of the best balance is commonly referred to as a "trade-off analysis" or a "trade study," or more generally as "trade-off analytics." Therefore, trade-off analytics are needed to support sound project management and systems design decisions.

The authors have a long history of performing system trade-off analyses. We participated in a book project at the request of the International Council on Systems Engineering (INCOSE)[2] Corporate Advisory Board (CAB). In 2015, the CAB identified the lack of effective trade-off analysis methods as a key concern and requested help in documenting best practices. Our book project was also motivated by the need to formalize systems engineering trade-off analysis to help make it an integral part of the systems engineering life cycle. The textbook[3] provides essential elaboration of the Decision Management Process in ISO/IEC/IEEE 15288, Systems and software engineering - System life cycle processes, the INCOSE Systems Engineering Handbook, and the Systems Engineering Body of Knowledge.[4] In addition, the textbook provides a comparison of several techniques and illustrates a variety of techniques applied to different life cycle stages.

Trade-off analytics are often applied as part of researching systems engineering methods, processes, and applications. We decided to review the state-of-the-practice of trade-off analytics in the recent literature to investigate several characteristics of interest, such as the engineering domains that use trade-off analytics, the types of analyses, the variables used, and what methods are used. We conducted a study of papers published in refereed engineering journals and refereed conferences.

The paper is organized as follows: the first section introduces the topic, the second section identifies our research questions, the third section describes our literature search methodology, the fourth

TABLE 1 Research questions were grouped into three categories

Type of questions	Research questions
Bibliographic analysis	A. What journals and conference proceedings publish the trade-off analysis papers?
	B. What are the publication trends over time?
	C. Where was the first author from?
	D. How highly cited are the publications?
	E. What percentage of the papers mention risk?
Categorical analysis	F. Is the paper an application or a case study?
	G. What engineering domains use trade-off analysis?
	H. Are the models used single or multiple objective?
	I. What types of models are used? Deterministic, probabilistic?
	J. What analysis methods were described in the papers?
	K. What percent of the papers use cost in the trade-off?
Bibliometric analysis	L. What are the most common terms in the abstracts?
	M. How interrelated are the terms in the abstracts?
	N. What are the most cited references?

section provides our findings, the fifth section discusses the implications for academics and practitioners, and the final section provides the conclusions.

2 | RESEARCH QUESTIONS

We structured our literature search to answer the research questions found in Table 1. We grouped the questions by the type of analysis required to answer the question. The first group of questions are easily answered using bibliographic analysis. The second group of questions required content analysis and developing categories to structure the answers to each question. The third group of questions uses bibliometric analysis to answer each question. Bibliometrics is the use of statistical methods to analyze the relationships between publications.

3 | LITERATURE SEARCH METHODOLOGY

In this section, we describe the structured literature review and analysis we performed to answer the research questions. We selected Web of Science (WOS) as our research source, because it includes the major engineering journals and refereed conference proceedings where we expected to find papers describing trade-off analytics for system decision making. Web of Science[5] includes tagged data fields for the author names, document (paper) title, publication (journal) name, keywords, abstracts, citation counts, cited references, publisher, publication year that provide information to answer our research questions.

The research methodology is shown in Figure 1. The first step in our process was keyword screening to determine a reasonable number of papers for further analysis. The second step was to review the abstract and review the paper to determine if the paper described an application or case study. Third, we performed a full text analysis to verify a quantitative trade-off analysis was performed and to support answering the research questions. Fourth, the research questions and the results of the analysis were entered into an Excel spreadsheet to allow binning the paper information into categories that would provide useful insights for the research questions. Fifth, we used a Pivot table to develop the tables and charts presented in the findings. Sixth, we used a software tool for constructing and visualizing the bibliometric networks. The visualization of the bibliometric networks is used to analyze the abstracts to determine the most common terms for methods and measures and for application domains in the abstracts and to determine the co-occurrence interrelationships among these terms. Finally, we analyzed the cited references for the papers we selected to determine the most cited references.

3.1 | Process overview

We used WOS key word screening to identify 260 papers. Preliminary paper review reduced the 260 papers to 145 unique papers that were applications or case studies. We verified that a quantitative trade-off analysis was performed to further reduce the 145 papers to 98 papers. We analyzed the 98 papers to answer our research questions.

3.2 | Keyword screening

We used the WOS and limited our search to papers published in 2005 or later to obtain recent papers and reduce our search to a feasible number of papers. To select higher quality papers, we limited our search to journal papers and refereed proceedings. Table 2 provides the keyword search that we used first identify several thousand possible papers, listed in Table 2 as "not used," which we then analyzed to select 260 papers then ultimately screen to 98 papers. The three

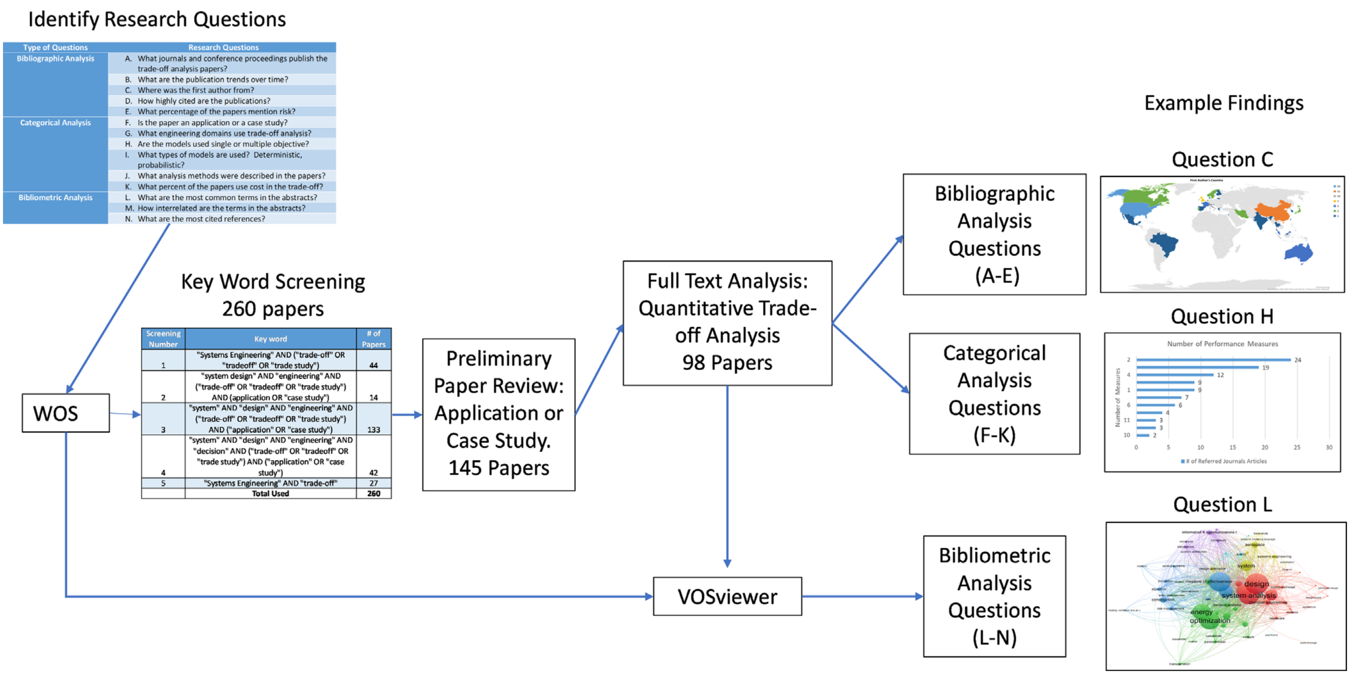

FIGURE 1 Research methodology used bibliographic, categorical, and bibliometric analysis

TABLE 2 Web of science keyword search found 260 papers. The number of unique papers about applications or case studies were 145. Full text analysis narrowed the review to 98 papers included in our analysis

Screening number	Key word	Number of papers	Full text analysis	Included
1	"Systems Engineering" AND ("trade-off" OR "tradeoff" OR "trade study")	44	35	24
2	"system design" AND "engineering" AND ("trade-off" OR "tradeoff" OR "trade study") AND (application OR "case study")	14	12	9
3	"system" AND "design" AND "engineering" AND ("trade-off" OR "tradeoff" OR "trade study") AND ("application" OR "case study")	133	98	65
4	"system" AND "design" AND "engineering" AND "decision" AND ("trade-off" OR "tradeoff" OR "trade study") AND ("application" OR "case study")	42	0	0
5	"Systems Engineering" AND "trade-off"	27	0	0
	Total Used	**260**	**145**	**98**
Not used	"engineering" AND ("trade-off" OR "tradeoff" OR "trade study")	2230		
Not used	"system design" AND ("trade-off" OR "tradeoff" OR "trade study")	416		
Not used	"system design" AND ("trade-off" OR "tradeoff" OR "trade study")	324		
Not used	"system" AND ("trade-off" OR "tradeoff" OR "trade study")	19795		
Not used	"system" AND ("trade-off" OR "tradeoff" OR "trade study") AND ("application" OR "case study")	2743		
Not used	"system" AND "design" AND ("trade-off" OR "tradeoff" OR "trade study") AND ("application" OR "case study")	1224		

most common words we used were trade-off, tradeoff, and trade study. Using systems engineering and one of these three words resulted in 44 papers. Broadening our search to system design and engineering added another 14 papers. Adding system, design, engineering, and application or case study added 133 papers. Comparing screen 4 and 3, we see that 42 of the 133 papers used decision in their title or abstract. Comparing screens 5 and 1, we see that trade-off analysis was the most common term of the three terms we used. The “not used” screening rows in Table 1 show the number of papers using screening criteria that were outside of the scope of this paper.

3.3 | Preliminary paper review

The second step in our literature review process was to remove duplicate papers; verify the paper was a journal, journal early access, or refereed proceeding; and to review each abstract and scan each paper to verify the paper described an application or case study. If the paper used at least one of the terms “application” or “case study,” that the paper was categorized accordingly. For the remaining papers, if a DM or client was identified, the paper was categorized as an application. If not, the paper was categorized as a case study. From the fourth column of Table 2, we can see this preliminary paper review reduced the 260 papers to 145 papers.

3.4 | Full text analysis

The most time-consuming part of our literature search was the full text analysis to verify that the paper included a trade-off analysis and obtain the information to answer several of the research questions. We listed the 145 papers in rows of a summary matrix. We verified that a quantitative trade-off analysis was performed. Our definition of a quantitative trade-off analysis was at least one graph in the paper that illustrated a trade-off between at least two variables. This analysis reduced the 145 papers to 98 papers.

We used the columns of the matrix to enter full text analysis data from the paper reviews. Several research questions required binning into categories. The category labels were determined initially by the first author and refined by the discussion with the author team. The team agreed with the classification labeling. Table 3 column 2 provides the full text analysis methods we used for the remaining 98 papers. For these questions, the binning method in described in the 3rd column of Table 3. Some of the binning was straightforward. A few of the binning methods require some explanation. First, is the binning of the paper as a deterministic or probabilistic method. If the paper used one of these terms, we used the authors' identified category. The remaining papers were reviewed and binned into the most appropriate category. Second, the analysis method was determined using the following categories: Optimization, Multi-Criteria Decision Analysis, Decision Analysis, Simulation, Statistics, and Mathematical Models. Paper were categorized as Mathematical Models if they that did not fit in the other five categories, but they did use mathematical equations to describe their

TABLE 3 Full text analysis and binning methods. Seven of the questions were answered by Full Text analysis

Research question	Full text analysis method	Binning method
C. Where is the first author from?	Identified the country of the first author from the paper.	Binned by country.
F.Is the paper an application or a case study?	Used authors terms when provided. Applications had to have a study sponsor.	Application or case study.
G.What engineering domains use trade-off analysis?	Identified the engineering domain described in the paper.	Binned the domains into domain categories.
H.Are the models used single or multiple objective?	Labeled each paper single or multiple objectives based on the number of objectives in the trade-off analysis.	Single or multiple objectives.
I.What types of models are used? Deterministic, probabilistic?	Listed the method the authors described in their paper.	Binned the methods by deterministic or probabilistic.
J.What analysis methods were described in the papers?	Listed the analysis method identified in the paper.	Binned the analysis methods into analysis categories.
K.What percent of the papers use cost in the trade-off?	Searched for “cost” and verified that it was used as a trade-off variable.	Binned to two categories: cost used, and cost not used.

modeling approach. Finally, when binning the papers, we identified the primary method used in the trade-off analysis. For example, an optimization model to identify the tradespace that used one or more mathematical models would be categorized as an optimization model.

3.5 | Constructing and visualizing the bibliometric network

VOSviewer is a software tool for constructing and visualizing bibliometric networks.[6] We exported the full record data fields from the WOS for the 98 selected papers and used VOSviewer to analyze the abstract record fields for co-occurrences of most common terms for methods and measures and for application domains. Co-occurrence is the occurrence of two terms in the same paper. The output from VOSviewer included a count of the number of occurrences across all of the abstracts for each of the terms; a network mapping of the co-occurrences of pairs of terms, where the link weights between each pair of terms in the map is number of co-occurrences of the two terms; and a clustering of the terms that maximizes a function based an association strength normalization of the link weights.[7] VOSviewer provides the capability to automatically identify terms from abstracts using a four-step process.[8,9] The first step performs part-of-speech tagging (i.e., identification of verbs, nouns, adjectives, etc.) using the Apache OpenNLP toolkit (http://incubator.apache.org/opennlp/) and uses a linguistic filter to identify noun phrases. The second step selects the most relevant noun phrases, which VOSviewer identifies the most relevant noun phrases using the Kullback-Leibler distance between distribution of (second order) co-occurrences over all noun phrases and the overall distribution of co-occurrences over noun phrases. The third step maps and clusters the terms, and the fourth step produces visualizations of the results.

The initial application of this four-step process produced 3361 terms. The VOSviewer tool provides a thesaurus mechanism to manually combine similar terms and eliminate terms that do not have high discriminatory power within the context of our bibliometric analysis. An example of combining similar terms was to combine the "ilities" based on previous work in systems engineering on combining these terms[10–13] by mapping them to the term "suitability" in the thesaurus. An example of a term that was eliminated is "paper," which occurred 3072 times in the abstracts. After inspecting the abstracts, it was confirmed that in no instance did it refer to the manufacturing application domain of producing products from the pulp of wood. Through a series of iterations, the 3361 terms were reduced to 70 terms that were either methods and measures or were application domains.

3.6 | Analyzing the cited references

We exported the reference list for the 98 papers from the WOS database and imported them into an Excel spreadsheet to identify the most highly cited references, and to reveal the methods and measures and the application domains covered by the identified references.

3.7 | Limitations

We identified several limitations related to our study that are worth summarizing.

1. The scope was limited to only published papers included in WOS using our key words.
2. The authors stated methodology was used without review of the appropriateness or quality of the models.
3. Other analyses may have been performed that were not described in the paper.
4. Many applications are not published.

We believe that (a) is not limiting, as WOS covers most publications in science, engineering, and technical fields. WOS also has similar coverage in these fields as Scopus, so we feel comfortable using only WOS. For (b), we assume that the authors and peer reviewers have adequately reviewed the papers, so it is unnecessary for us to dig into this further. For (c), we focused only on the parts of the paper that met our requirements to be defined as a trade-off using at least two variables. For (d), we assume that many applications of trade-off analytics are not typically published in the literature, but instead occur in the course of doing systems design and systems engineering that does not produce publications that are submitted for peer review in the open literature. We are thus limited only to those situations where authors thought they had work that was of sufficient interest or had significant findings that were submitted, reviewed, and accepted for publication.

4 | FINDINGS

The findings are presented by type of question, followed by answering each of the research questions of their respective type, from Table 1.

4.1 | Bibliographic analysis questions

The findings for the bibliographic analysis questions are the following.

A. What journals and conference proceedings publish the trade-off analysis papers?

Appendix A identifies the publisher and the engineering journals for the 98 papers surveyed in this literature search.

B. What are the publication trends over time?

Figure 2 shows that publications have been generally increasing over time.

C. Where was the first author from?

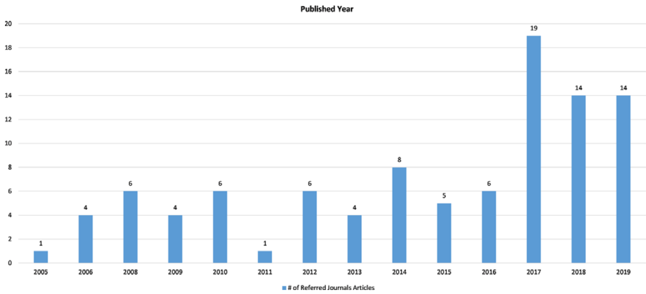

FIGURE 2 Publications by year. Publications are generally increasing over time

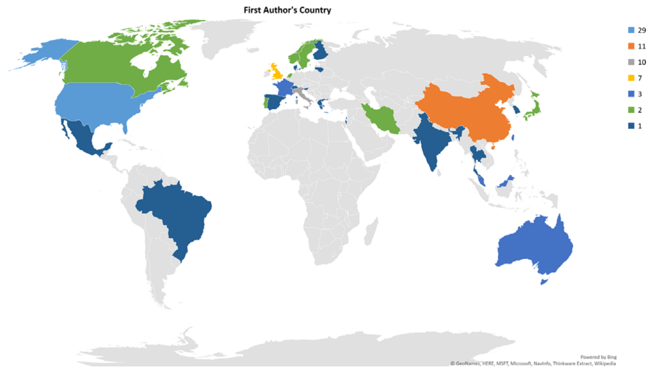

FIGURE 3 The first authors were from seven countries

Figure 3 shows the country of the first author. The first authors were from seven countries. The largest number of authors were from the U.S., China, Italy, and the U.K.

D. How highly cited are the publications?

The maximum citation count was 45. The average citation count was 10 (Figure 4).

E. What percentage of the papers mention risk?

Forty four of the 98 papers mention risk (Figure 5).

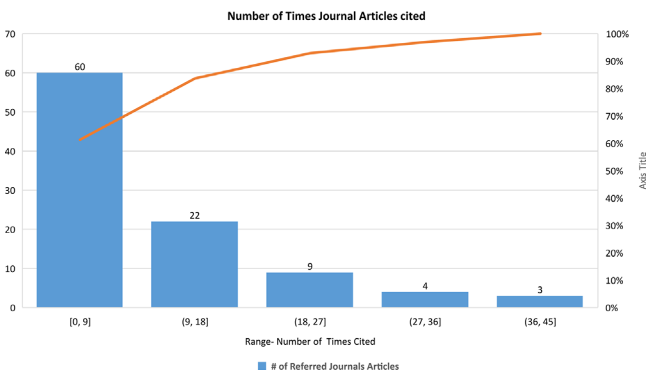

FIGURE 4 Paper citations. This figure shows a Pareto chart for citations

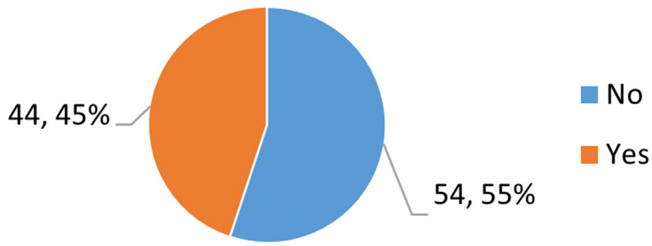

FIGURE 5 Papers that discuss risk. Only 44 of the 98 papers mention risk

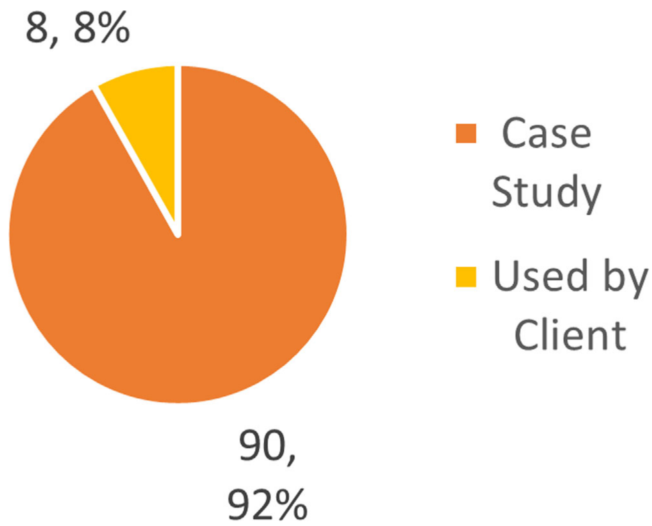

FIGURE 6 Case studies versus applications. Case studies were 92% of the papers

4.2 | Categorical analysis questions

The categorical analysis findings are as follows.

F. What number of papers were applications and case studies?

Eight papers were applications, and 90 papers were case studies (Figure 6).

G. What engineering domains use trade-off analysis?

The number of papers by domain is shown in Table 4. Trade-off Analysis is used in many engineering domains. The three largest domains are Aerospace, Manufacture, and Energy.

H. Are the models used single or multiple objective?

Not surprisingly, most of the trade-off analyses use multiple objectives. Figure 7 shows that nine have a single objective and 89 have multiple objectives. The number of performance measures ranged from 1 to 14. Figure 8 shows the distribution.

I. What types of models are used? Deterministic, probabilistic?

TABLE 4 Engineering domains. The papers were binned into 18 engineering domains. Aerospace, manufacturing, and energy had the largest numbers of papers

Engineering domain	Number of referred journal papers
Aerospace	14
Manufacturing	13
Energy	12
Chemical Engineering	10
Construction	10
Automation	7
Water Management	7
Information Systems & Software	6
Cyber -Physical	3
Electronics	3
Marine	2
Mechanical Engineering	2
Medical	2
Transportation	2
Waste Management	2
Agriculture	1
Energy	1
Optical Engineering	1
Total	**98**

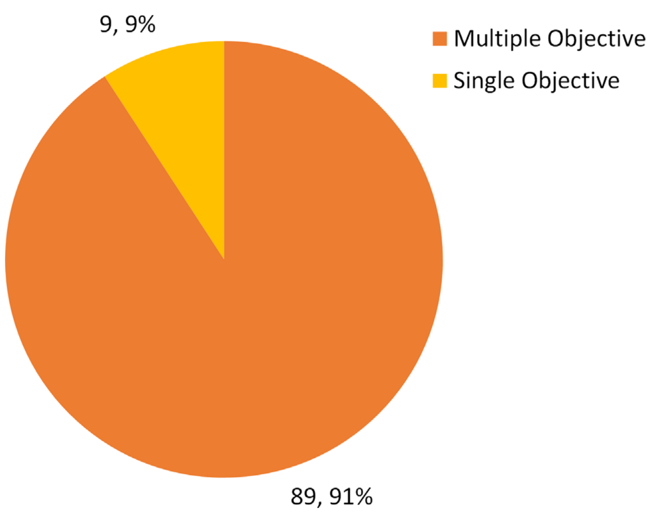

FIGURE 7 Single or multiple performance measures. Ninety-one percent of the papers used multiple performance measures

Many of the papers were deterministic. Only 28 of the papers used probabilistic methods. The methods are shown in Table 5.

J. What analysis methods were described in the papers?

Table 5 provides the analysis methods used by the authors. The most common methods are Optimization and Multicriteria Decision

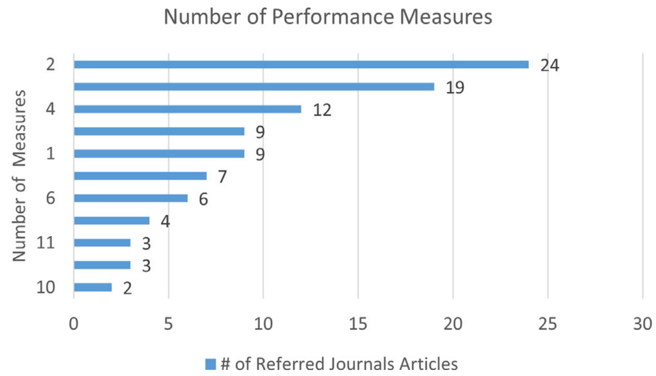

FIGURE 8 Number of performance measures. Performance measures ranged from one to fourteen

TABLE 5 Analysis type and methods. Seventy one percent of the papers were deterministic. The most common methods were optimization and multi-criteria decision analysis/decision analysis

Analysis type	Methodology	Number of papers
Deterministic 70	Optimization	26
	Multi-Criteria Decision Analysis	18
	Decision Analysis	11
	Mathematical Models	6
	Simulation	5
	Statistics	4
Probabilistic 28	Optimization	8
	Multi-Criteria Decision Analysis	5
	Decision Analysis	9
	Mathematical Models	1
	Simulation	3
	Statistics	2
Grand Total		98

Analysis/Decision Analysis. The Decision Analysis papers use techniques based on the axioms of decision analysis. The Multicriteria Decision Analysis papers use multicriteria methods that are not based on the axioms of decision analysis. Mathematical models are models not using the other five methodologies, for example, a physics model.

K. What percent of the papers use cost in the trade-off?

Of those papers, 61% used cost as one of the trade-off variables. In our binning, costs refer to only monetary costs (Figure 9).

4.3 | Bibliometric analysis questions

The findings for the bibliometric analysis are presented using a network map. The network map produced by VOSviewer is shown as Figure 10. The size of each of node is proportional to the number of

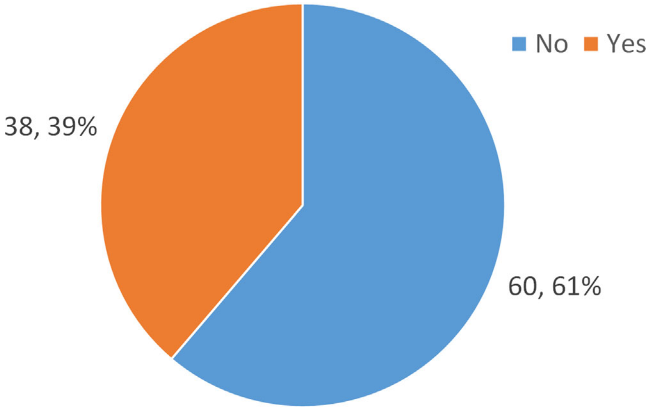

FIGURE 9 61% of the papers used cost as a trade-off variable

occurrences of each of the 70 terms that were in our thesaurus of terms. The links in the network are constructed based on of the co-occurrences of pairs of terms, where the link weights between each pair of terms in the map is number of co-occurrences of the two terms. The colors of the links and nodes are based on the categorizing the terms into six clusters that maximizes a function based on the link weights. We analyzed the quantitative results underlying the visual map to determine the most common terms and the interrelationships of the terms.

L. What are the most common terms in the abstracts?

There were 2684 total occurrences of the 70 terms in the 98 paper abstracts, which equates to slightly more than 27 terms per abstract on the average. Table 6 shows the terms that account for 70% of the total

TABLE 6 Most common 70 terms in abstracts

Category	Term	Number of occurrences
Application domains	Energy	154
	Aerospace	57
	Construction	54
	Chemical engineering	50
	Information and communications technologies	44
	Manufacturing	43
Methods and measures	Design	194
	Systems methodology	181
	System analysis	170
	Optimization	165
	Measure of performance	129
	Cost	117
	Modeling	102
	System	100
	Case study	67
	Requirement	57
	Measure of effectiveness	56
	Multiple objective	49
	Lifecycle stage	45
	Objective	43

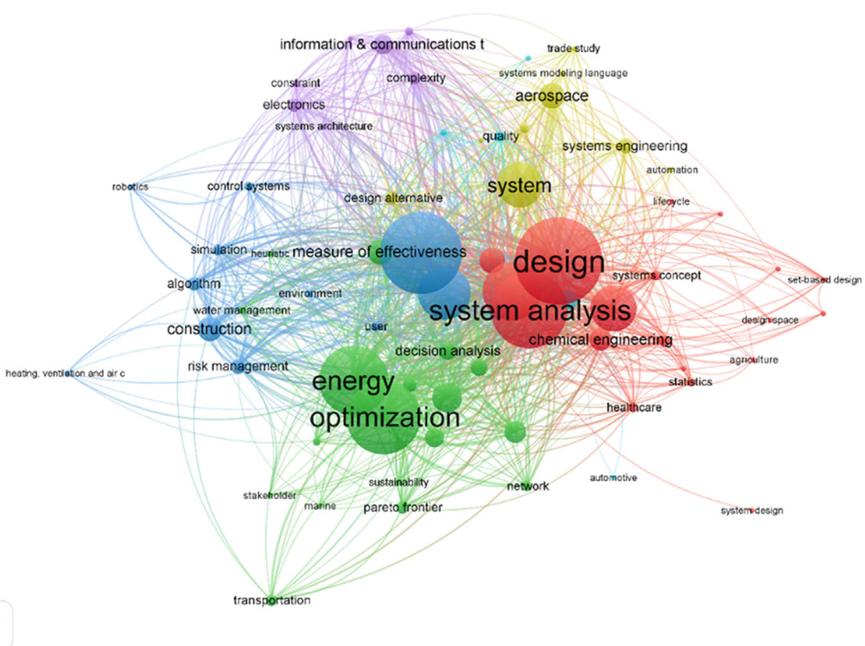

FIGURE 10 VOSviewer term map. The size of each of node is proportional to the number of occurrences of each of the 70 terms. The colors of the links and nodes are based on the categorizing the terms into six clusters that maximizes a function based on the link weights

TABLE 7 Term co-occurrence clustering results

	Co-occurrence clusters					
Category	**1**	**2**	**3**	**4**	**5**	**6**
Application domains	chemical engineering (50) healthcare (21) biosystems (6)agriculture (5)	energy (154)transportation (26) water management (16)marine (9)	construction (54) environment (16) robotics (9) heating, ventilation, and air conditioning (4)	aerospace (57)information technology (20)automation (6)	information and communications technologies (44) electronics (30)cyberphysical systems (19)	manufacturing (43)automotive (2)
Methods and measures	design (194) system analysis (170) measure of performance (129) modeling (102) requirement (57) uncertainty (26) systems concept (22) statistics (18) lifecycle (6) design space (4) set-based design (4) systems science (4) tradespace (3) system design (2)verification and validation (2)	optimization (165) case study (67) measure of effectiveness (56) multiple objective (49) objective (43) decision analysis (39) system property (38) waste management (30) pareto frontier (28) network (23) scenario (17) sustainability (12) heuristic (9)stakeholder (9)	systems methodology (181) cost (117) lifecycle stage (45) risk management (33) algorithm (30) simulation (24) control systems (21)user (21)	system (100)systems engineering (34) design alternative (28) trade study (11) systems modeling language (8)tradeoff analysis (5)	complexity (28) constraint (15) suitability (11)systems architecture (11)	quality (24)decision making (15)industrial engineering (3)

occurrences of the terms. We further identified each term as belonging to one of two categories, "Methods and Measures" or "Application Domains." The most common terms have to do with "Methods and Measures," and the top three terms are associated with design thinking or systems thinking. The appearance of optimization is not surprising, as most scholarly publications that appear in the WOS database tend to prefer papers that demonstrate a prescriptive approach based on an optimization method as opposed to an approach based on heuristics. A somewhat surprising result is that the most frequently occurring application domain term was "energy" with "aerospace" being second most frequent domain for the papers that address trade-off analytics.

M. How interrelated are the terms in the abstracts?

Figure 10 is a mapping produced by VOSviewer four-step process that depicts the interrelationships among the terms and the categorization of the terms into clusters.

To understand the interrelationships of the terms, we manually assigned all the terms in each cluster to one of two categories, "Methods and Measures" or "Application Domains," as shown in Table 7. The color coding of terms in Table 7 is the same color coding used to highlight clusters in Figure 10, and the number in parentheses following each term is the number of occurrences of each term used to determine the size of the nodes in Figure 10.

When interpreting our summaries, it is important to note that in our thesaurus, we mapped source terms that describe satisfaction of end-user need to the term measure of effectiveness, and we mapped terms that describe measurable engineering characteristics to measures of performance.

- The domains of chemical engineering, healthcare, biosystems, and agriculture are more likely to refer to concepts such as design, systems analysis, measures of performance, etc. than the other domains. Of note is that papers in these domains are more likely to refer to uncertainty and statistics that the other domains.
- The applications areas of energy, transportation, water management, and marine systems are more likely to describe employing optimization, measure of effectiveness, multiple objectives, objectives, and decision analysis.
- The construction; environment; robotics; and heating, ventilation, and air conditioning domains have an emphasis on systems methodologies, cost, lifecycle stages, and risk management, which may be an indication that the focus of these application domains is more aligned to program management rather than to system design and engineering.
- The application domains of aerospace, information technology, and automation are most aligned to systems engineering approaches and do not necessarily align themselves with formal analytic approaches such as optimization and decision analysis.
- The information and communications technologies, electronics, and cyberphysical systems areas emphasize complexity, constraints, and

TABLE 8 Most highly cited articles. The top four references are to articles on evolutionary algorithms and a specific subclass of evolutionary algorithms known as genetic algorithms

Title	Count
A fast and elitist multiobjective genetic algorithm: NSGA-II	11
Evolutionary multi-objective optimization in water distribution network	3
Genetic algorithms for least-cost design of water distribution networks	3
Multiobjective evolutionary algorithms: A comparative case study and the	3
Multiobjective genetic algorithms for design of water distribution	3
Trade-off between total cost and reliability for Anytown water	3

suitability measures. They also emphasize systems architecture, which may be their approach to handling these three categories.

- The manufacturing and automotive domains emphasize quality, decision-making processes, and industrial engineering approaches, which most likely is due to their emphasis on lean and six-sigma paradigms.

N. What are the most cited references?

The most highly cited articles listed among the 2159 articles that were cited by the 98 papers are listed in Table 8. There were 62 articles that were only cited twice, and the remaining articles were only cited once.

- The top four references are to articles on evolutionary algorithms and a specific subclass of evolutionary algorithms known as genetic algorithms.[14]
- Four of the top five references belong to the application domain of water management.
- The very low number of common citations and the presence of only one application domain among the most highly cited articles are an indication that there is very little commonality of methods and measures across 20 application domains that we identified.
- Among the 62 articles that were cited twice, there are a significant number of articles that refer to evolutionary algorithms and other optimization methods. This supports our previous conclusion that scholarly publications that appear in the WOS database are more likely to focus on optimization (see Table 5) as opposed to heuristic methods for decision-making in system design.
- Complexity of trade-off analytics causes nonlinearity which leads to the use of genetic and evolutionary algorithms.

5 | INSIGHTS FOR SYSTEMS ENGINEERING

As our literature survey demonstrates trade-off analysis can be found in almost every engineering domain. System design and systems engineering involve making decisions with multiple stakeholders with diverse and, potentially conflicting, objectives. As more and more data become available with digital engineering, big data, and data science, trade-off analytics will be an increasing important tool for engineers. We believe there are several insights from the literature survey for educators and practitioners.

5.1 | Educators

Academics are usually the authors of case studies. Some of the case studies are publishable abstractions of applications they worked on for research sponsors or consulting clients. We offer several insights. First, we need a common language for trade-off analytics. As evidence of the lack of common language for trade-off analytics, we cannot even agree on the spelling of trade-off versus trade off—not to mention trade-off analysis, trade study, or tradespace exploration. Second, textbooks and case studies need substantive examples of trade-off analytics. Surprisingly, the references include very few engineering textbooks. Fourth, there is a surprising lack of probabilistic analysis that is required to understand the risk in system design and systems engineering. Fifth, there is a dearth of case studies that use multiple methodologies and assess the pros and cons of the methods. Case studies offer a great way to explore and compare different methods on the same problem. One exception to the finding is a case study that demonstrated that Monte Carlo simulation outperformed a genetic algorithm in finding better Pareto optimal solutions in minutes versus hours.[15]

5.2 | Practitioners

We believe that practitioner should use sound mathematical techniques that explore the fully tradespace. Some specific additional recommendations: First, consider all relevant stakeholder objectives, and expect to have multiple objectives when you have multiple stakeholders. Second, review the literature to learn what others have done for trade-off analytics in your engineering problem domain. Third, understand the advantages and disadvantages of alternative trade-off analysis techniques.[16] Fourth, if long time horizons, uncertainty, and risk are involved, consider using probabilistic techniques. Fifth, write a paper to share your applications with educators and practitioners even if you must develop a notional case study to avoid revealing sensitive information. Consider partnering with an academic who has more incentive to obtain a publication.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX A

Papers by Publisher and Journal/Conference Name

Publisher	Journal/Conference	Number of papers
American Chemical Society	Industrial & Engineering Chemistry Research	3
American Institute of Aeronautics and Astronautics	Journal of Aircraft	3
American Society of Civil Engineers	Journal of Computing in Civil Engineering	2
	Journal of Construction Engineering and Management	1
	Journal of Transportation Engineering Part-A Systems	1
	Journal of Water Resources Planning and Management	7
American Society of Mechanical Engineers	Journal of Mechanical Design	3
Cambridge	Artificial Intelligence for Engineering Design Analysis and Manufacturing	1
Earthquake Engineering Research Institute	Earthquake Spectra	1
Elsevier	Advances in Space Research	1
	Applied Energy	2
	Automation in Construction	1
	Biosystems Engineering	1
	Computer-Aided Design	1
	Energy and Buildings	1
	Engineering	1
	Engineering Structures	1
	Heliyon	1
	Information and Software Technology	1
	International Journal of Production Economics	2
	Journal of Computational Design and Engineering	1
	Journal of Industrial and Engineering Chemistry	1
	Journal of Manufacturing Systems	4
	Marine Policy	1
	Mathematics and Computers in Simulation	1
	Performance Evaluation	1
	Reliability Engineering and System Safety	1
Emerald	Engineering Construction and Architectural Management	1
	Journal of Engineering Design and Technology	1
Institute of Electrical and Electronics Engineers	IEEE Access	3
	IEEE Systems Journal	1
	IEEE Transactions on Automation Science and Engineering	1
	IEEE Transactions on Biomedical Engineering	1
	IEEE Transactions on Engineering Management	1
	IEEE Transactions on Industrial Informatics	1
	IEEE Transactions on Very Large-Scale Integration Systems	1
	IEEE Transactions on Smart Grid	1

(Continues)

Publisher	Journal/Conference	Number of papers
Multidisciplinary Digital Publishing Institute	Energies	1
	Remote Sensing	1
	Sustainability	1
	Systems	1
Pergamon-Elsevier Science	Chemical Engineering Science	3
	Computers and Chemical Engineering	2
	Energy	1
	Expert Systems with Applications	1
	Renewable Energy	1
Royal Aeronautical Society	Aeronautical Journal	1
Sage Publications	Journal of Defense Modeling and Simulation-Applications Methodology Technology	1
	Proceedings of The Institution of Mechanical Engineers Part E-Journal of Process Mechanical Engineering	1
Springer	Interactive Systems: Design, Specification and Verification	1
	International Journal of Advanced Manufacturing Technology	1
	Journal of Electronic Materials	1
	Requirements Engineering	1
	Research in Engineering Design	2
	Software and Systems Modelling	1
	Structural and Multidisciplinary Optimization	1
	Theoretical Foundations of Chemical Engineering	1
Taylor & Francis	Engineering Optimization	2
	International Journal of Computer Integrated Manufacturing	1
Tech-Science Press	Computer Modeling in Engineering and Sciences	1
The Institution of Chemical Engineers	Chemical Engineering Research and Design	1
The International Society for Optics And Photonics	Journal of Micro-Nanolithography Mems And Moems	1
	Optical Engineering	1
The Japan Society of Mechanical Engineers	Journal of Advanced Mechanical Design Systems and Manufacturing	1
Wiley	American Institute of Chemical Engineers Journal	1
	Environmental Progress	1
	Environmental Progress and Sustainable Energy	1
	Journal of Applied Polymer Science	1
	Structural Control and Health Monitoring	1
	Systems Engineering	4
	Total	**98**

APPENDIX : Cited Articles

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