A Bibliographic Multi Theme Review of Cybersecurity, AEC and 3D Printing: Learnings and Way Forward for the AEC Industry

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Abstract –

The exponential growth in both three-dimensional printing (3DP) and cybersecurity (CS) poses a significant challenge for the change-resistant architecture engineering and construction (AEC) industry. Despite growing research related to any of these fields combined, there is a research gap associated with their combination, particularly with themes and topics in conjunction with AEC and 3DP. To address this and the larger knowledge gap of a methodology for multi-theme review, this research a) develops a generic multi-theme bibliometric analysis and b) validates the developed methodology with the help of three themes mainly CS, AEC, and 3DP. To achieve this, data was collected from Scopus and analyzed using Biblioshiny. The results emphasize the need for further imminent research in combinations of CS and AEC and more particularly in CS, AEC, and 3DP, where the growth rate is null despite growing research in individual domains mentioned. It is also noted from the findings that interdisciplinary research within these domains call for increased collaboration. This should not only motivate researchers in these aspects but assist stakeholders in identifying the need, work towards addressing this and more importantly, enhancing collaborative efforts.

Keywords –

Cybersecurity; 3D Printing; Construction Industry; Text-mining; Biblioshiny; Threat Modeling

1 Introduction

Architecture, engineering, and construction (AEC) industry significantly contributes to the global economy accounting to 13% of the global GDP [1]. The resources required have also been exceptionally high at about 50% of the gross global resource usage [1]. Its adversity to change, innovation, and lack of productivity [1] is the motivation for its growing connection with three-dimensional (3D) printing (also referred to as 3DP), along with the reduction in labor [1][2], waste [2] and pollution [1], time [1][2] and costs [1], increased worksite safety and the opportunity to explore complex geometries [1][2] as they do not require formwork [3].

Furthermore, the United Arab Emirates (UAE) has initiated the "Dubai 3D Printing Strategy", aiming to have 25% 3D printed buildings in Dubai by 2030 [4]. Large-scale applications of 3DP are not novel, beginning from 1997 with contour crafting, freeform and additive manufacturing, rapidly progressing to whole residential buildings and bridges, making this target much more feasible [5]. Some of the existing structures constructed using 3DP, many of which were designed for a service life of 50 years or greater are as follows [2]: 1) Non-load bearing walls of a single-storey student house in Denmark in 2021; 2) A two-storey office building in UAE built in 2019; 3) A double-storey residence in Germany in 2021 constructed; 4) An army barracks hut in USA in 2019; 5) A one-storey residence in the Netherlands in 2021; 6) The Striatus footbridge in Italy in 2021.

Although research in these two fields namely AEC and 3DP has gained significant interest over the years, the cybersecurity (CS) aspect in either of them is still not given as much importance [6] owing to the limited studies conducted during the construction process and much of the focus taken up by the design stage and the post-construction stage [7]. This knowledge gap is what makes it crucial to understand how these three fields are connected and explore the future possibilities due to their assimilation.

2 Literature Review

AEC Industry has struggled to identify and protect against cyber-attacks. Studies suggest that among the

common targets of cyber-attacks, AEC industry is the third in the list [8]. Research also shows that only 25% of the construction firms have prioritized cyber-security issue [8]. The theft of Interserve construction firm's employees' personal information has cost around £11m due to a cyber-attack [9]. Moreover, according to an annual report by an insurance giant Hiscox, almost half of United Kingdom (UK) construction firms have suffered from cyber-attacks, ranking it as the fifth most vulnerable industry for the second consecutive year [10]. A more specific example of this in 3DP would be the attempt of hackers to steal data on Hadrian X, a one-armed robotic bricklayer in Australia [11]. [12] also cautions of increased risk of cyberattacks due to the exponential increase in the adoption of machine learning and robotics in the AEC industry. It is thus evident that more studies should focus on increasing the awareness, perception, implementation, framework, standard, threat modeling, attack maps, countermeasure of the cyber security related aspects to protection data, reputation, operations, and business at large.

3DP technology is still in its infancy in the AEC industry along with the investigation of CS aspects within the domain. The CS research within AEC and its susceptibility to cyberattacks can be studied with the help of existing standards, tools, frameworks, and case studies from other domains since the process is similar. The slow adoption of digitization and CS in AEC is arguably due to lack of awareness, reputation, and competition of the AEC industry, among many other reasons. Some specific reasons particularly for 3DP within AEC industry include requirement of special material for printing, lack of standards and regulations, limitations of 3D printers on-site, and operation and management of 3D printers [13][14]. Many characteristics of the AEC industry itself also contributes to this slow pace, such as its project-based, uniqueness, conservative, change-resistant and fragmented nature, with various stakeholders' involvement at different phases of its life cycle [14][15][16]. Thus, it must be noted that these cannot be directly adopted given the inherent characteristic limitations as mentioned above.

As an example, one of the methods of cyberattack during the 3DP process is acoustic side-channel attacks by using smartphones, which makes use of the Internet of Things (IoT) to steal confidential Intellectual Property (IP) information during 3DP. Using laboratory testing methods, some researchers were able to affirm IP leakage through the side channels of the 3DP process by using commercial off-the-shelf smartphones [17]. Sabotage attacks originating from the cyber domain can affect the physical domain and compromise systems' structural integrity potentially resulting in severe safety risks. Subtle variations in the sub-process can cause changes in the 3DP's parameters [18]. Other vulnerabilities include man-in-the-middle attacks to maliciously alter the ".STL" or the G-code file [19], which can compromise the quality of the product since the ".STL" file contains the design data, which is then sliced by a slicer software into layers as a G code to feed into the 3D printer [20]. [21] carried out a case study of cyberattack on the .STL file, wherein they altered the design to add a void, which impacted the specimen's strength. Other attributes that can be a target of such attacks are printing speed, the thickness of the layer, infill of the printing path [22]. Direct parallels can be drawn within the AEC industry and there can be several learnings for the same. Similarly, rapid digitalization incorporates several technologies such as the internet of things (IoT), building information modeling (BIM), machine learning (ML), robotics, and artificial intelligence (AI), which are also susceptible to cyberattacks. Examples of such attacks on HVAC (heating, ventilation, and air conditioning) and BMS (Building Management System) systems, unauthorized access, stealing construction plans, and breaching of sensitive and personal data are detailed in [7]. These can be seen mainly in OSC (Offsite Construction) and prefabrication [23], however, these are not separately detailed to consider AEC as the broad theme.

Table 1: Previous Studies Focus & Limitations

Study Focus	Limitations
3DP/AM & AEC [24][25]	Focused on systematic mapping, cannot be directly adapted for bibliographic analysis.
3DP/AM & AEC [26]	Focused on systematic literature review to identify gaps only.
CS & AEC [7]	Restricted to two themes and does not identify multiple permutations and additional themes of interest.
AEC & Industry 4.0 [27]	Focused on systematic mapping, cannot be directly adapted for bibliographic analysis.
IoT & Smart Health Research [28]	Lack of clear framework in the methodology to conduct multi-theme analysis.
Servitization & manufacturing [29]	Focused on systematic literature review to identify gaps only.

To overcome such gaps and obtain learnings and a way forward for the future of the industry and research community, researchers resorted to summarizing and synthesizing existing literature on the respective subject. For example, the text mining method is utilized, and relevant bibliometric data is analysed. Table 1 lists some of the multi-theme reviews conducted both in the fields of interest, and others. Given their review, it is evident that no such analysis has been carried out for all three fields namely CS, AEC, and 3DP, which is the goal of

this paper. Furthermore, there is no clear framework that can be directly adapted to our study, as eident in Table 1. Thus, the proposed methodology contributes to the existing body of knowledge by providing a general, systematic, easy to use multi-themed bibliometric analysis framework that can be applied for more than 2 themes irrespective of context and applications. The objectives of this study therefore are to a) develop a general research methodology for multi-theme bibliometric review, and b) validate the developed methodology with the help of three specific themes of interest in the current context namely CS, AEC, and 3DP.

3 Methodology

Figure 1 shows all the steps in the proposed methodology. Broadly categorized, the methodology employs a bibliometric approach to address the research objective of this study. Each of these steps is detailed in the sub-sections below.

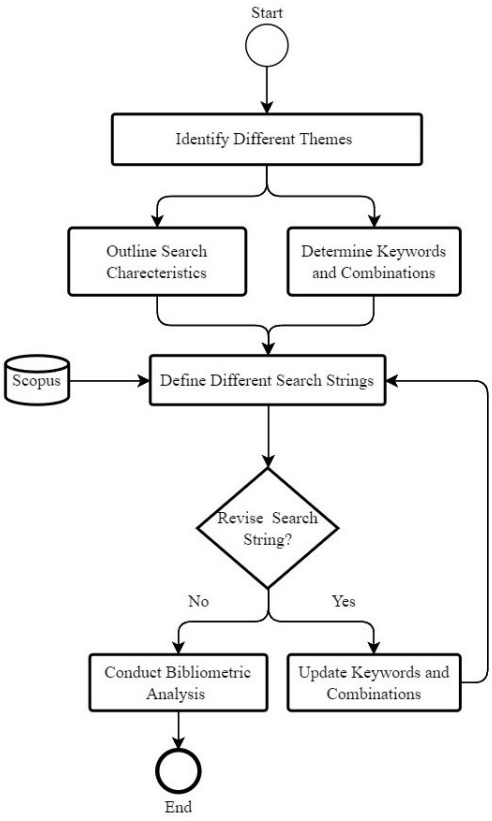

Figure 1: Overview of Proposed Methodology

3.1 Identify Different Themes

The objective of this step is to identify different themes of interest pertaining to the context, application, and need. In the current context, three themes namely CS, AEC, and 3DP were chosen. Each of these terms is described briefly below. 3DP, also known as additive manufacturing or digital fabrication technology, is an emerging technology that creates physical objects from a geometrical representation through successive addition of materials. There is a mass increase of 3DP technology in the production of open-source design in agriculture, automotive and locative industries, aviation industries, including the construction industry. [30][31]. AEC, widely known as construction, refers to the creation of physical infrastructures as well as the maintenance and repair of the existing structures [32]. CS is a significant concern of every infrastructure and organization. It includes practical measures to protect information, data, and networks against any internal and external threats.

With the rise of 3DP technology in the AEC industry, CS has become a critical factor [33]. It has to be noted that the primary concern within CS is threat modelling (TM) and countermeasures. Although these are sub-topics within the main theme of CS, in the latter stages of analyses in Section 4, it is also considered a theme of interest for further investigation and exploration. These themes will act as the foundation for further analyses and potentially pave the way for future research.

3.2 Outline Search Characteristics

Once the themes are identified, the immediate next step is to outline the search characteristics along with the selection of databases to conduct the search. In this study, Scopus was used as it is a vast database of abstracts and citations created by Elsevier, indexing more than 90% of journals and 70% more sources than WoS [34][35]. Since papers in combined fields are limited, Scopus is a better choice as it has 20% more coverage than WoS, including more journals despite their low impact [36].

Advanced search was done in Scopus to define the search characteristics due to the complexities of the search. Table 2 outlines the summary of the search characteristics and is described briefly below along with the rationale. The initial searches showed a significant of the papers published were in English, so the language was set to English, which also helps to verify the relevancy of the results. Since books and book chapters were both selected, the book sources from the first page results of the combination of 3DP and AEC, limited once only to books, and then only to book chapters, were used to compare them. Since there were no repeating sources, both document types were included. Mainly, the year range of 1950 to 2022 was chosen, as at this timeline, technology, and automation became of interest due to the third industrial revolution [37], and to keep the results consistent, the current year is excluded. The Boolean OR is used to group the words within the same domain, AND for combinations, AND NOT for excluding irrelevant words. It aims to find papers with at least one word from each domain. Wildcard is a tool in Scopus used to include

all similar words with different endings, for example, "3D print*" was used to include 3D printer, 3D printing, 3D printed, etc. All searches were carried out for selected keywords within the title, abstract or keywords of papers.

Table 2: Summary of Scopus Search Characteristics

Criteria	*Option*
Search type	Advanced search
Languages	English
Document type	articles, conference papers, reviews, book chapters, conference reviews and book
Timespan	1950 – 2022
Booleans used	AND, OR, AND NOT
Advanced search tool used	Wildcard (*)
Searches within	TITLE-ABS-KEY (Article title, abstract and keywords)

3.3 Determine Keywords and Combinations

In this step, relevant keywords and combinations need to be determined for the different themes identified in section 3.1. In addition, a list of exclusion words must be determined for irrelevant words that were found while manually checking for the search results. Different combinations of the chosen themes and topics can be determined subject to their relevance and applicability.

Table 3 outlines the summary of the keywords for the three main themes (CS, AEC, 3DP) along with the additional topic (TM) that was chosen for this study given its significance as discussed earlier. For example, regarding the exclusion words, the words hackneyed and hacksaw were taken from previously published papers and checked within these strings. Since they did bring up irrelevant papers, they were also added to the exclusion list. Section 3.4 discusses this further. Table 4 represents the 11 different combinations that were carried out. Although more were possible or done, due to the same results for those combinations, or irrelevancy, it was limited to only those shown in the table.

3.4 Define Different Search Strings

The objective of this step is to define the search string based on the identified based on the above steps (sections 3.1, 3.2, and 3.3. For example, the search for each combination from Table 4 was conducted using keywords from Table 3, the results of which were exported as a CSV file. The results from Scopus were last updated on 11th December 2023.

3.5 Update Keywords and Combinations

The immediate next step after conducting the search using the strings defined in Section 3.4 is to update the keywords and combinations based on the results. The purpose of this step is to refine the keywords, exclusions, and combinations and improve the search results. The following sub-sections discuss significant results of the same.

Table 3: Keywords & Exclusions for Each Theme

	Keywords	**Exclusions**
3DP	3D print, 3DP, additive manufacturing, additive fabrication, contour craft, extrusion-based printing, extrusion-based technology, rapid prototyping technology, rapid manufacturing, solid freeform fabrication, automated printing, three dimensional print	
AEC	(architecture, engineering, and construction), AEC, aecfm, (architecture, engineering, construction, and facility management), aeco, (architecture, engineering, construction, and operations), construction industry, construction sector	automatic exposure control, advanced eye center, array eddy current
CS	Cyberattack, Cyberbreach, Cybercrime, Cyberresilience, Cyberthreats, Cybervulnerability, Cyberspace, Cyberphysical, Cybersecurity, Sabotage attack, hack	Hackneyed, hacksaw, hackling
TM	Threat Models, digital model, Risk propagation, Vulnerability assessment, Counterattacks, Countermeasure analysis, Safety measures, Anti-hacking, Smart grid, Network security, Intrusion detection, Blockchain, Cloud-BIM	

3.5.1 3DP and AEC

Initially, more words under AEC, such as 4IR or Fourth Industrial Revolution, and under 3DP, such as automat, freeform were used, which resulted in papers under nursing, veterinary, and neuroscience. For example, "A study to determine the effects of industry 4.0 technology components on organizational performance" and "Freeform 3D printing of vascularized tissues: Challenges and strategies". Even the word construction, paired with 3D printing, resulted in several irrelevant papers, due to its usage as a verb. All these words were removed, and construction was replaced with words like construction industry and construction sector. The acronym AEC also brought up a few unwanted papers, but since they were fewer in number, those were added to the exclusion list.

Table 4: Combinations & Results

No	3DP	AEC	CS	TM	Results
1	■				107,664
2		■			71,635
3	■	■			632
4			■		54,306
5			■	■	13,110
6	■		■		186
7	■	■	■		2
8	■		■	■	34
9	■	■	■	■	1
10		■	■		55
11		■	■	■	15

3.5.2 3DP and CS

In this combination, papers like "A new technology to machine bimetal band saw" due to the use of Hack* could not be removed, so the keywords hacksaw, hackneyed, and hackling were excluded using AND NOT.

3.5.3 3DP and AEC and CS

This combination yielded 4 results, two of which are repeated and are simply the conference rather than an article within the conference. So, they were removed manually after exporting from Scopus.

3.5.4 3DP and CS and TM

Initially, TM was split into two domains, one for TM, and another for countermeasures. Due to the lack of papers, since the same results were obtained for both, the keywords in both groups were merged into one group, currently named TM. The threat model VAST was also a keyword, along with other types of threat models. However, since VAST also brought up results where it is used as an adjective, it was removed. The others were also removed since their presence made no difference in the results.

3.5.5 Other Combinations

The remaining combinations used the updated list from the previous searches, so no more modifications were done to them. Nonetheless, they were also checked for further improvement if required.

3.6 Conduct Bibliometric Analysis

Once the keywords and combinations are finalized, meaning no further refinement in search strings is required, updated results are extracted as per Section 3.4 and finally, bibliometric analysis of these results need to be conducted. In the current context, after all the searches were completed, the csv files exported from Scopus were used in Biblioshiny to analyse them. Significant parameters such as annual publication, annual growth rate, authorship, average citation per year, and frequent words from Biblioshiny were analysed and discussed.

4 Results and Discussion

This section discusses the results obtained from Scopus using the keywords and combinations as discussed in Section 3.3. It also discusses the results obtained from the analysis of Biblioshiny for specific themes and combinations as mentioned in Section 3.6.

4.1 Scopus Search Result

The Table 4 in Section 3.4 shows the number of total publications within the study timeframe for each combination. As can be observed, the publications within CS theme are approximately half of that in both the 3DP and AEC (i.e., construction) domains, with even fewer papers understandably when focused on the TM. A significant decrease was observed for combinations of these themes, with the least two-theme combination for 3DP and Construction, and only one when combining all domains. The one paper that comes up when all domains are combined is "Threat Modeling in Construction: An Example of a 3D Concrete Printing System", which discusses the use of a threat model in 3DCP.

4.2 Annual Scientific Production and Growth Rate

The total number of publications for each year is discussed in this section. Due to the large difference in the number of publications, they were divided into two parts, one for the main themes and another for the combinations. Although TM is a topic within CS, due to the high volume of papers and it being the primary focus within CS, it was also considered for further analysis and discussion.

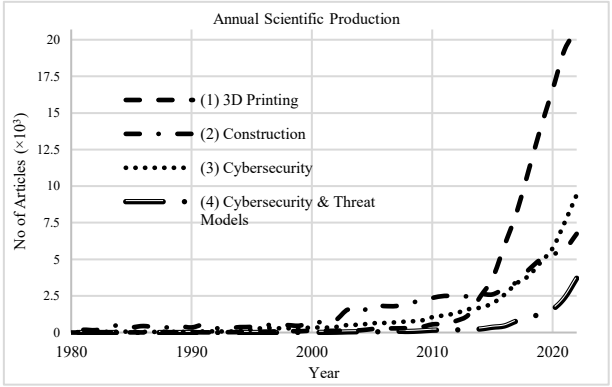

Figure 2: Annual Production for Main Themes

Figure 2 shows the annual production for the main themes. A noteworthy observation is that production for

all of them began to pick up after the year 2000, with 3DP growing the fastest and TM the slowest. Both AEC and CS have a steady growth of approximately 10%, as seen in Figure 4. This suggests the growing prominence and relevance of 3DP further corroborating the theme selection for this study.

Since the numbers were smaller for combinations relative to the main themes, particularly in the earlier years and due to the exponential growth, logarithm (log) of the cumulative annual production for each was considered to better view and is shown in Figure 3. Additionally, the years that had only 1 publication cumulatively were removed as log (1) is equal to 0. It can be observed that all the graphs have a general increasing trend. Although the combinations of 3DP and CS with Construction (no 5 and 10) began in 2002, other combinations begin much later, especially those combinations that involve three domains namely no. 7, 8 and 11. This further emphasizes the motivation of this study.

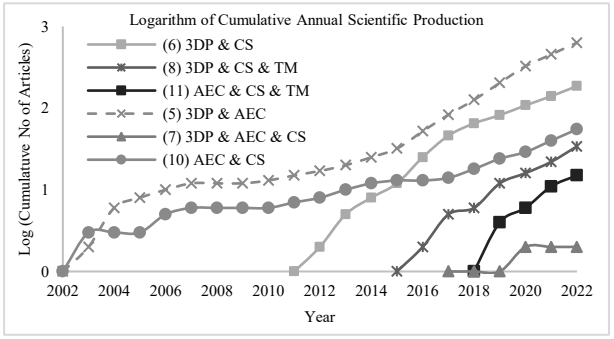

Figure 3: Annual Production for Combinations

Figure 4 shows the annual growth rate (AGR) in percentage. As discussed, for no. 7 and 9, the number of publications were 2 and 1 respectively, hence the null growth rate. The AGR for the combinations is high despite the low number of publications because of the rapid growth of publications over the recent years. This shows that current research is largely focused on either 3DP and AEC or 3DP and CS and does not consider all three domains together.

4.3 Authorship

For each combination, the number of documents with single authors, multiple authors, and authors' collaboration internationally per article were analysed in this section and shown in Figure 5. The number of single-authored publications were huge for Construction and CS with 14,134 and 13,858 respectively, while for the combinations, it was between 0 and 43. It was in the mid-range for 3DP and TM, at 4,949 and 1,368 respectively. The co-authored publications for all were in the range of 1 and 4.8. Since both single and co-author values use the number (left) axis, it was difficult to properly observe the co-author result in the same plot. Thus, the log of single-authored publications was used instead. The international co-authorship is in percentage and uses the secondary (right) axis.

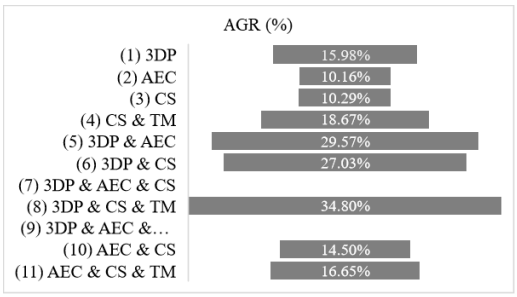

Figure 4: Annual Growth Rate (AGR)

Publications with single authors are relatively high for the main domains, but 0 for combinations of 3 domains. This may be due to the limited number of papers within these areas. As opposed to this, co-authored documents are published for all 11 areas of study. The international co-authorship, which refers to the authors of a co-authored publication being from different countries, is also 0 for two of the combinations, no (7) and (9). This is expected since there are only 1-2 papers from them. However, a positive trend is observed where combinations of domains encourage researchers' collaboration across these disciplines.

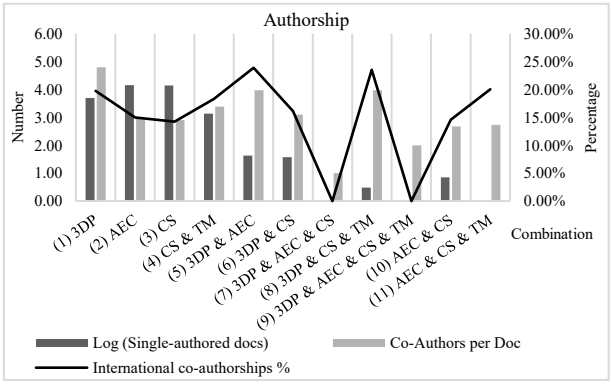

Figure 5: Single, Co-, & International Authorship

4.4 Average Citation per Year

The citations were also divided into two parts, one for the main themes in Figure 6 and another for the combinations in Figure 7. Figure 6 shows a steady increase for all of the themes, with the highest in 3DP. Similar to the annual production, the 3DP graph has a higher increase than the rest. TM, although beginning in

year 1994, increased rapidly and caught up with Construction and CS, both of which had a steadier rise since. The peaks at various years may be due to inconsistent research or lack of collaboration and interest [38]. These peaks have reduced in recent years as more research is conducted consistently every year.

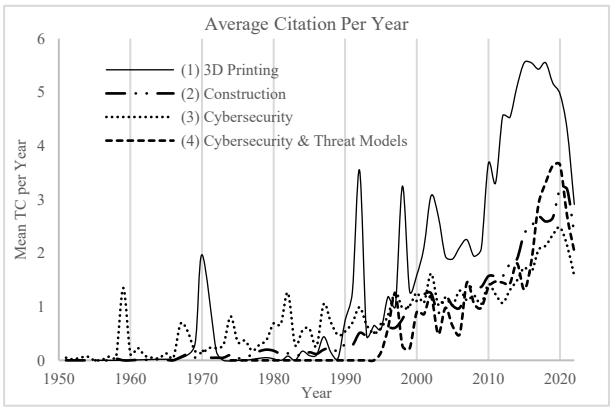

Figure 6: Annual Citation for Main Themes

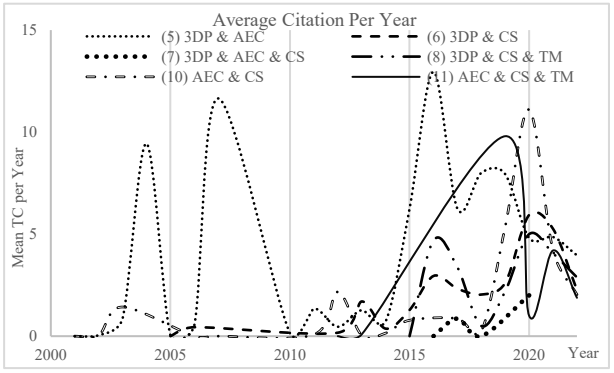

Figure 7: Annual Citation for Combinations

Figure 7 shows the citations for the combinations. Since there are not many papers for them, the citation graphs look randomized, with the exception of combination 6 which appears to have a more consistent increase than the others.

4.5 Most Frequent Words

A list of frequent words for each search were taken from Biblioshiny and displayed in the form of a Venn diagram in Figure 8. Although the combinations had a smaller result, any repeating keywords were placed in the intersections, according to the characteristics of a Venn diagram. These keywords not only highlight the current trends but will also help identify future research topics. As can be seen in Figure 8, a lot of the keywords that combine all three themes have to do with CS, such as risk assessment, security and unauthorized access. The extent of involvement desired from each domain is still missing, which requires combining the intersections of any two domains with others so more of those appear at the centre.

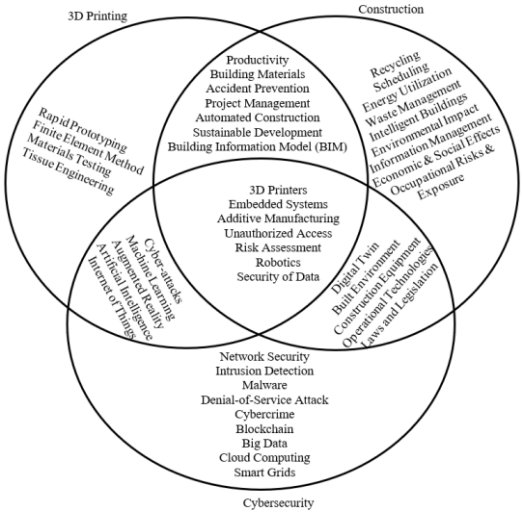

Figure 8: Frequent Words

5 Conclusions

This study developed and validated a multi-theme bibliometric analysis methodology addressing the critical knowledge gap in literature. Specifically, the three most significant and crucial themes of CS, AEC, and 3DP were investigated and analyzed. Results from the extensive, comprehensive and thorough bibliometric analysis suggest that a) CS-related topics such as security, privacy, and risk assessment are gaining momentum in the recent past but research within in AEC industry still lacks sufficient studies, b) combination themes have more co-authored papers than single-authored papers suggesting for collaborative approach on multi-disciplinary research endeavors. c) annual growth rate (AGR) was higher for combinations excluding AEC than otherwise, and zero for the 3DP-CS-AEC combination, emphasizing the need for further CS research within the AEC research community and more significantly for those including 3DP and AEC. A general roadmap for future research is discussed in Table 5 based on the observed recently published studies (now), ongoing research efforts (next), and what AEC community can aim at (future). The future roadmap in particular was derived from the summarized literature from the CS community.

One of the limitations of this study was that a) due to the large number of results for the original themes, it was practically not feasible to check for duplicates and remove them all b) due to the capacity of Biblioshiny, some of the papers were omitted during the analysis. Future research can be aimed at addressing these limitations and further comprehensively exploring all the

parameters of the Biblioshiny and also other software and databases to compare the results.

Table 5: Roadmap to Future Research

Now	Next	Future
Currently, much of the focus in 3DP is within the manufacturing industry, in terms of CS [17][18].	Although parallels can be drawn from manufacturing to AEC, it is required to have real case studies in the AEC to study its impact directly, due to the uniqueness of each project within AEC.	It is very likely that once focus is shifted to CS in AEC and 3DP jointly, with tested case studies, new issues of implementing 3DP into AEC will arise, which will require innovative solutions to be tackled.
3DP is generally vulnerable to hacking and tampering due to its digital reliance [19][20][22].	These vulnerabilities need to be tested in settings similar to the projects in AEC and holistically, rather than targeting only one aspect of it at a time.	Large-scale application of 3DP in AEC will require new research methodology and countermeasures to overcome.
Digitization of the AEC industry at present, such as adopting BIM, IoT, and ML already expose it to numerous threats of cyberattacks [7].	Evolution of cyberattack threats in digitized AEC that also integrated 3DP technology.	Countermeasures and threat models to combat these threats, which is only done in one paper (Garcia de Soto and Shibly, 2020). It is also the only paper that falls under 3DP-CS-AEC as seen from the results in Section 4.

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