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Technology Forecasting of Unmanned Aerial Vehicle Technologies through Hierarchical S-Curves

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ABSTRACT

This study aims to propose a technology forecasting approach based on hierarchical S-curves. The proposed approach uses holistic forecasting by evaluating the S-curves of sub-technologies as well as the main technology under concern. A case study of unmanned aerial vehicle (UAV) technologies is conducted to demonstrate how the proposed approach works in practice. This is the first study that applies hierarchical S-curves to technology forecasting of unmanned aerial vehicle technologies in the literature. The future trend of the UAV technologies is analysed in detail through a hierarchical S-curve approach. Hierarchical S-curves are also utilised to investigate the sub-technologies of the UAV. In addition, the technology development life cycle of technology is assessed by using the three indexes namely, (1) the current technological maturity ratio (TMR), (2) estimating the number of potential patents that could be granted in the future (PPA), and (3) forecasting the expected remaining life (ERL). The results of this study indicate that the UAV technologies and their sub-technologies are at the growth stage in the technology life cycle, and most of the developments in UAV technology will have been completed by 2048. Hence, these technologies can be considered emerging technologies.

Keywords: Unmanned aerial vehicle; Technology life cycle; S-curves; Patent analysis

1. INTRODUCTION

Evaluation of the defence technologies is vital for countries and defence companies in the current age. Decision-makers should analyse the technology development of defence technologies to make accurate decisions and funnel their budget into a proper technology due to the limited financial resources. The sustainability of defence technology production also substantially depends on efficient defence management, which can be possible by the analysis of defence technologies. Moreover, enterprises operating in the defence industry should determine the technologies that they need to channel their financial resources to ensure a strategic and sustainable competitive advantage.

Over the last two decades, Unmanned Aerial Vehicle (UAV) technologies have developed rapidly and are expected to generate extensive spillovers into other industry sectors[34]. These technologies have lower costs, smaller sizes, and extended capabilities[4]. An increase in the trends towards UAV technology leads to a worldwide diversification in the UAV-related sub-domain technologies.

Since the spillover effects of technological innovations in the military trigger developments in other civilian applications and uses, this means that UAV technology has a dual usage, making the technology a potential investible domain. UAV technologies are extensively used for military purposes, such as reconnaissance and surveillance missions, electronic intelligence activities. Besides, they are used for civilian purposes, such as agricultural activities, firefighting, and cargo transportation as well. For that reason, it can be stated that the UAV technologies are dual-use technologies. The concept of dual-use indicates that the technology is used both for military and civilian applications[5].

In this study, patent analysis is performed to analyse the UAV technologies. Patent analysis is extensively utilised for technology evaluation such as[55-57]. Patent analysis is commonly used for S-curves in the literature[6-8]. S-curves are also generally used to analyse the technology life cycle of the targeted technology as well as for the technology forecasting based on the patent data. Because S-curves are helpful in revealing the substitution of the former technologies with the novel technologies at the industry level. In addition, they assist managers in planning new technology development at the firm level[9]. S-curves can be used to determine the current stage of the technology, such as initiation, growth, and saturation as well. Moreover, it can be possible through using the S-curves to comment on a target technology regarding its potential investment alternatives in the future.

Unmanned aerial vehicle (UAV) technologies are cutting-edge defence technologies with dual-use for civil purposes. These technologies are composed of various sub-technologies. Funneling limited financial resources to the right sub-technologies is substantially significant for the firms in the defence industry. Thus, analysis of the UAV technologies could

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provide crucial signs related to their prospective technology direction as well as enabling decision-makers and technology managers with the latest information on the current situation of the technologies.

The development of a specific technology relies heavily upon various sub-technologies related to this specific technology. This signifies that the technology is mainly an aggregation of some sub-technologies in practice. Figure 1 illustrates a four-level nested hierarchy based on the study of Murman and Frenken[10].

It is not possible to evaluate technologies without analyzing subsystems. Previous studies merely assess the main system while neglecting the aggregation of numerous relevant subsystems[3]. Hence, the S-curve of the target technology should be evaluated together with the S-curves of its sub-technologies. In this study, hierarchical S-curves are used to analyse the S-curves of the UAV technologies and corresponding sub-technologies for the evaluation of technology. Analysis of technologies through hierarchical S-curves is relatively a new approach in the literature.

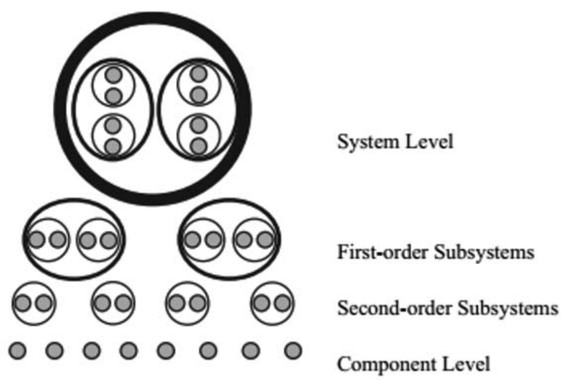

Figure 1. A four-level nested hierarchy[10].

2. LITERATURE REVIEW

UAV technology is one of the main emerging technology in the field of defence industry. The technology is being used for the Navies since 1985, while it is being used for the Land Forces since the 1990s, and the Air Forces from 1995 onwards (http://archive.defense.gov). UAV technology has advanced significantly in recent years[53]. Researchers have conducted many studies examine UAV technologies. Among these studies, Bone and Bolkcom[12] provided introductory information related to UAV technologies, compared unmanned and manned aircraft systems, and examined the UAV's background with their detailed technical features. In another study, Demir[13], *et al*. categorised the literature of UAV studies into technological and operational spheres and summarised an outline of basic research areas in the UAV domain. Takemura[14] investigated the legal aspect of the UAV operations and focused on international humanitarian law issues related to the use of UAV technologies. Chao[15], *et al*. reviewed small or micro-UAVs and examined commercial and research autopilot systems for these UAVs. In another study, Herwitz[16], *et al.* analysed the UAV technologies for agriculture surveillance. Tang[54], *et al.* proposed an online trajectory planning strategy for unmanned combat aerial vehicles. Wang[17], *et al*. introduced a system to be used for detecting and tracking vehicles in traffic via UAV technology. Chou[15], *et al*. used the UAV technology to get real-time aerial photos for disaster monitoring and disaster-relief operations. Furthermore, UAV technology is used for detecting the weed seedling[19], road detection and tracking[20], traffic monitoring[21], as well as for the remote sensing applications[22,23] logistics[24], assessment, and monitoring of environmental contamination[25].

In addition to the above-mentioned studies, researchers mostly concentrated on the technical features of the UAVs in the literature as well. Wang[26], *et al*. introduced a method for planning the three-dimensional path for low-flying unmanned aerial vehicles. Moreover, fuzzy logic-based studies are also conducted for the UAV technologies in the literature. Among these studies, fuzzy logic-based closed-loop strap down attitude system[27], adaptive neuro-fuzzy inference system based autonomous flight control[4], classical and fuzzy-genetic autopilot design[28], fuzzy adaptive tracking control within the full envelope[29], and a fuzzy inference system[30] are proposed for the UAV technologies. Details on the UAV technologies can be found in the studies of Valavanis and Vachtsevanos[31] and Blyenburgh[32]. Hence, there is a vast body of research in the literature regarding UAV technologies.

Furthermore, various studies related to technology forecasting have been conducted in the literature. Kang[37], *et al.* discussed the technology forecasting methods and their application areas in their studies. Moreover, the technology prediction methods used by various technology fields and the relationship between these methods were also investigated in this study[37]. Zhu and Porter[38] offered suggestions on how to make the data mining method rapidly and more effectively, within the scope of technology forecasting. In another study, Lim[39], *et al.* examined the development process of LCD technology through the data envelopment analysis method.

Besides, Chang[40], *et al*. researched the diffusion rate of technology by considering the citation status of patents. Relationships between patents are also investigated in this study. Jun[41], *et al.* proposed a technology prediction model using clustering methods. Moreover, in the study, potential technology trends were revealed by establishing a matrix based on the analysis of patent documents. Woon[42], *et al.* focused on the development of methods that could forecast technologies at the beginning of the growth stage according to the increase in the number of publications. In addition, they used automatically generated keywords in their research to enhance the reliability of the study.

There are several the key technologies related to UAV such as robotics advancements, machine learning advancements, artificial Intelligence advancements, human-machine interface advancements etc[58]. Fahey and Miller[58] prepared a US DoD unmanned vehicle roadmaps (2017-2042).

Choi and Jun[43] proposed a Bayesian approach using patent clustering to analyse potential technology developments in the industry. Lin[44], *et al.* put forward in their study, which makes a systematic technology forecasting analysis in the field of the third-generation communication industry that more accurate results can be obtained by integrating different methods in technology forecasting. Another study that addressed technology forecasting analysis in a holistic framework was presented by Porter[45], *et al.*. Besides, in the study, evaluations were performed on various technology forecasting methods. Yoon and Park[46] tried to present a more quantitative approach to technology forecasting by integrating Morphological analysis with citation analysis. In addition, the researchers applied the data mining method in the study. Plus, Jun and Lee[47] made a technology forecasting by patent analysis in the field of nanotechnology using the International Patent Codes (IPC) in their patent documents. Gershman[48], *et al*. investigated the impact of technological forecasting and technology roadmap on innovation development of organisations. Yoon and Lee[49] examined industry areas that are suitable for technology forecasting with patent analysis. Thus, various technology forecasting methods have been used in several studies.

However, upon reviewing the literature, it is noticed that the studies that have investigated the future trend of UAV technologies via technology forecasting methods based on patent data are relatively limited. Among these, Liu[33], *et al*. revealed the development trends of the UAV in China by using the patent analysis method and shed light on the existing setbacks for the development of UAV technology in China. Kim[34], *et al*. discussed the spillover effects of the UAV technology on the other industries by using patent citation data. In order to quantify the impact of UAV technology on the beneficiary industries via patent data, they presented an approach of two-mode network analysis. So, they established a matrix that demonstrated the technology-industrial spillover effects of UAV technology. Bae[35] assessed the technology and analysed Korea's competitiveness through performing UAV patent analysis. Considering the increased demand for UAV technologies across the world and potential usage alternatives in various sectors, Liu[50], *et al*. outlined the panorama of UAV technologies, particularly in China. They scrutinised the current advances in UAV technologies through analyzing patent data with the "patentometric" method, which works by harnessing the raw data of patent documents on the targeted domain. In addition, they tried to give an insight for entrepreneurs regarding the future trend of UAV technologies. The study of Um[51] has probed the trend in spatial information technologies, as a sub-dimension of UAV technologies, specifically in South Korea. The researcher used patent data in the targeted technology to perform technology forecasting. The study has revealed that UAV aerial photography technology has not reached the stage of completion, and it still has considerable potential, particularly in battery run-time[51]. Battsengel[52], *et al*. have investigated the technological trends in UAV Technologies using the latent Dirichlet allocation (LDA) method of topic modelling and network analysis. They have determined the yearly trends of topics in the last 18 years in UAV Technologies. Moreover, they categorised these topics as "hot topics" and "cold topics", indicating the relevance degree of these topics with the UAV Technologies. Yet, their study is limited to the patent documents in the Korea Intellectual Property Rights Information Service [52]. Also, both studies span just the last two decades, which is relatively a short period. Hence, it is considered that to reveal the development trend and trajectory of the UAV technologies more accurately, there is a need to investigate the UAV technology from an earlier date. Therefore, in our study, we used patent documents that had been published between 1790 and 2018.

It is noteworthy that various perspectives have been suggested by the scholars in a broad range with different issues from technical features of the UAVs to the International Law related to drones and from current drawbacks in the development of UAVs to the potential developments in the UAV technology. While some of the scholars investigated the engineering dimensions and technical features of the UAV technology, many others revealed mainly industrial breakthroughs in the UAV technology as well as its social impacts. However, as above-mentioned, the studies that have been performed to forecast the future trend of UAV technologies through patent analysis are relatively limited. Hence, in this study, the UAV technologies are analysed through a novel technology forecasting method that is mainly based on the hierarchical S-curves.

3. ANALYSIS OF THE UNMANNED AERIAL VEHICLE TECHNOLOGIES

3.1 Patent Data

A patent document involves various information related to a specific technology field such as title, inventor, abstract, International Patent Classification (IPC) Code, and publishing date. Therefore, one can conclude valuable data related to a specific technology by examining patent documents[36]. Experts use data acquired from patent documents for technology forecasting in a particular technology domain[1]. There are various patent databases (e.g., USPTO (the United States Patent and Trademark Office), Espacenet, WIPO (World Intellectual Property Organization), JPO (Japan Patent Office), etc.) used by researchers in the literature. The USPTO patent database is used in this study, as it has a user-friendly interface that can be accessible by everyone without limitation and has widespread usage for scientific research.

To perform accurate research on the patent database, the keywords should be selected meticulously. In the study, the following query is used to obtain the required patent documents based on Kim[34], *et al*..

TTL/ ("Unmanned aerial vehicle" OR "unmanned aircraft" OR "intelligent aerial vehicle" OR drone OR "remotely piloted vehicle" OR "unmanned aircraft system") OR ABST:("Unmanned aerial vehicle" OR "unmanned aircraft" OR "intelligent aerial vehicle" OR drone OR "remotely piloted vehicle" OR "unmanned aircraft system")

These keywords are used to search the "titles" and "abstracts" of the patent documents through the software of Acclaimip Patent and Research. The search includes the patent documents that have been published in the USPTO patent database until April 31, 2018. A total of 1140 patent documents are retrieved from the USPTO patent database. However, throughout the detailed examination of these patent documents, 31 patents are found to be documents related to the beekeeping and toy industry, which include "drone" terms either in their title or in their abstract. Upon the elimination of these irrelevant patent documents, the total number of UAV technology-related patent documents is 1109. Figure 2 illustrates the technology forecasting of UAV through hierarchical S-curves.

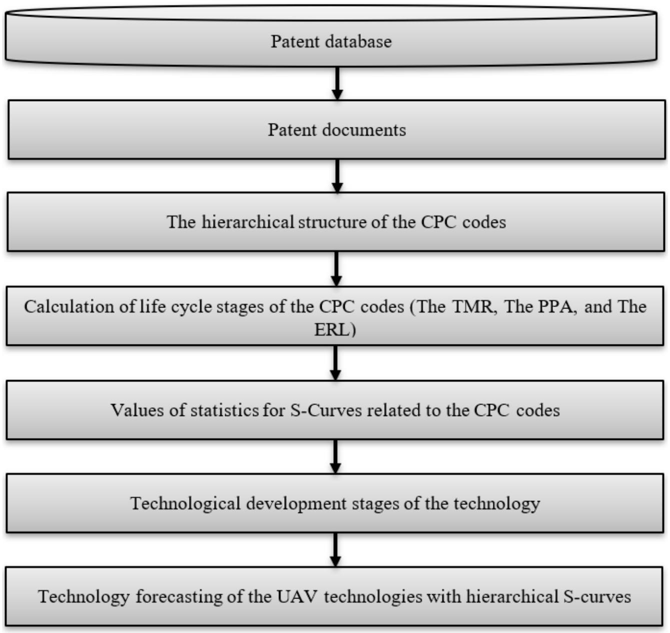

Figure 2. Technology forecasting of UAV through hierarchical S-curves.

3.2 Application of Hierarchical S-Curves to Unmanned Aerial Vehicle Technologies

In this section, the logistics growth model is performed to generate the hierarchical S-curves for the Technology Forecasting of unmanned aerial vehicle technologies. The logistics growth model is extensively used in the literature as it has the minimum average value of the absolute percentage of error (MAPE). The LogletLab4 software is used to form the S-curves in the study. Equation 1 is calculated based on the logistics growth model.

$$Y(t) = \frac{K-d}{1+e^{-r(t-t_m)}} + d \quad (1)$$

where,

K= saturation capacity (level)

t_m = time in which the logistics growth curve reaches half of its curve (middle time parameter)

d= initially the default amount of patents

r= the logistic growth rate or steepness of the curve

Yoon[2], *et al.* suggested using three novel analyses in terms of the technology life cycle for developmental stage analysis. They are (1) identifying the current technological maturity ratio (TMR), (2) estimating the number of potential patents that could be granted in the future (PPA), and (3) forecasting the expected remaining life (ERL). Figure 3 shows a developmental stage analysis by using growth curves. In this study, these three crucial analyses are also performed to delve into the details of the hierarchical S-curves of unmanned aerial vehicle technologies.

The calculation of TMR, PPA, and ERL of a target technology can be performed using Equation (2), Equation (3), and Equation (4)[2]:

$$TMR_{(t)} = \frac{K_{(t)}}{K} \quad (2)$$

$$PPA_{(t)} = K - K_{(t)} \quad (3)$$

$$ERL_{(t)} = T_{(k)} - T_{now} \quad (4)$$

where,

$K_{(t)}$ = the number of cumulative patents at time t.

K = saturation level.

$T_{(k)}$ = the year that the number of accumulated patents is expected to reach k x K (k is the threshold value ($0 \leq k \leq 1$).

The first two indices (TMR and PPA) can be simply calculated using the saturation level K of the growth curve[2]. TMR can take a value between 0 and 1 ($0\leq$ TMR ≤ 1). The TMR value indicates the degree of technological development. Therefore, as the TMR value increases towards "1", the technology approaches the end of its life cycle. Figure 4 shows the S-curve of the UAV technology. The TMR and The PPA of the stage of technology development can act as an early warning in terms of the technical focus for further R&D. Furthermore, the ERL shows when the technological advances in the technology will have been mostly completed[2].

As shown in Fig. 4, the saturation level is 4332. $K_{(2017)}$ is 1109 since the patent documents that have been published in the USPTO patent database until April 31, 2018, are 1109.

$$TMR_{(2017)} = \frac{K_{(2017)}}{K} = \frac{1109}{4332} = 25.6\% \quad (5)$$

$$PPA_{(t)} = K - K_{(t)} = 4332 - 1109 = 3223 \quad (6)$$

The values of statistics related to the S-curve of UAV technologies are presented in Table 1. The TMR value of UAV

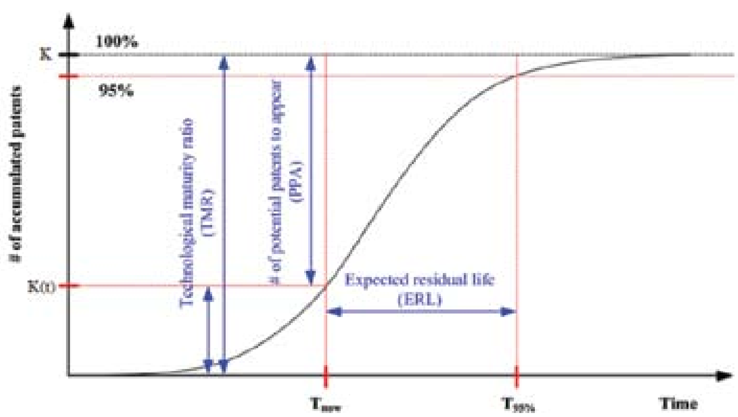

Figure 3. Developmental stage analysis using growth curves[2].

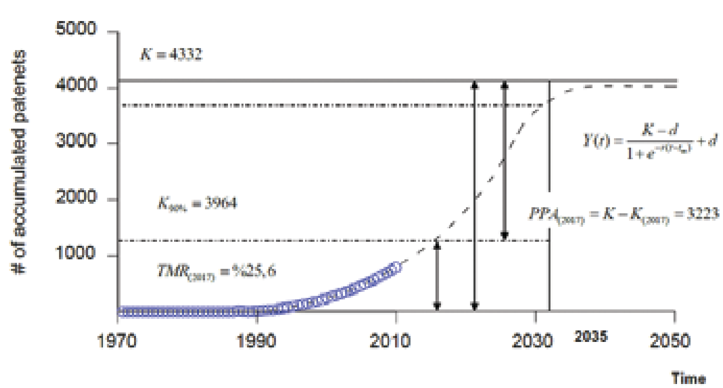

Figure 4. S-Curve of UAV Technology

Table 1. Values of statistics

d	K	tm	r	R^2	1%	10%	50%	90%	99%
0.000	4332	2022	0.183	0.972	1997	2010	2022	2035	2048

d: initially the default amount of patents; K: saturation capacity (level); tm: time in which the logistics growth curve reaches half of its curve (middle time parameter); r: the logistic growth rate or steepness of the curve; R2: the goodness of fit.

Technology is 25.6%, so the technology is still in its growth phase. The TMR value will have reached 50% by 2022. This finding indicates that the technology will have completed 50% of its life cycle as of 2022. Hence, the UAV technology has started to develop rapidly from 2018 onward. As seen from Table 1, the midpoint of the S-curve is 2022. The curve becomes steeper gradually after 2022. This points out that technology is still improving. In other words, it can be suggested that the technology has not passed to the saturation stage yet. It can be noticed that the steepness of the curve will start to decrease in 2035 (see Fig. 4). This implies that 90% of the technology life cycle will have been completed by 2035 (see Table 1).

d: initially the default amount of patents; K: saturation capacity (level); tm: time in which the logistics growth curve reaches half of its curve (middle time parameter); r: the logistic growth rate or steepness of the curve; R2: the goodness of fit.

According to the S-curve in Fig. 4, it is expected that the UAV technology will pass to the saturation phase from 2035 and reach the saturation point in 2048 (see Table 1). For that reason, it is considered that most of the developments in UAV technology will have been completed by 2048. UAV technology was estimated to have an ERL of 13 years at the beginning of 2018 (2035-2018). The estimated PPA of the UAV technology is to be 3223 patents. "*The TMR is a ratio measure of technological maturity, while the PPA is the number of potential patents that are expected to be granted in the future by further technological advances*"[2].

Developments in a technology's sub-technologies affect the development speed of that technology[3] Thus, the sub-technologies that have the most correlation with technology play a significant role in determining the life cycle of that technology. In order to identify which subclass technologies are related to the UAV technology, CPC codes of the patents included in a total of 1109 patent documents that have been published in the field of UAV technology were analysed. The top 10 CPC codes, which are determined by examining the first four digits of the CPC codes and included in the 1109 patent documents, are presented in Fig. 8. A patent might have more than one CPC code. Therefore, the number of patents corresponding to a CPC code may exceed the total number of patents (1109). The hierarchical structure of the CPC codes is presented in Fig. 5 and illustrated in Fig. 6.

Figure 5. Top 10 CPC Classes of UAV Technology.

Figure 6. The hierarchical structure of the CPC codes.

Table 2. The Top 10 CPC codes of UAV Technology*

CPC Code	Description	# of Patents
B64C	Aeroplanes; Helicopters	33062
G05D	Systems for Controlling or Regulating Non-Electric Variables	46164
G08G	Traffic Control Systems	16244
B64D	Equıpment for Fitting in or to Aircraft; Flying Suits; Parachutes; Arrangements or Mounting of Power Plants or Propulsion Transmissions in Aircraft	23693
G01S	Radio Direction-Finding; Radio Navigation; Determining Distance or Velocity by Use of Radio Waves; Locating or Presence-Detecting by Use of The Reflection or Reradiatıon of Radio Waves; Analogous Arrangements Using Other Waves	60835
G06T	Image Data Processing or Generation, in General	76379
H04W	Wireless Communication Networks	142919
H04N	Pictorial Communication, e.g. Television	238037
G06K	Recognition of Data; Presentation of Data; Record Carriers; Handling Record Carriers	92995
B64F	Ground or Aircraft-Carrier-Deck Installations Specially Adapted for Use in Connection with Aircraft; Designing, Manufacturing, Assembling, Cleaning, Maintaining, or Repairing Aircraft, Not Otherwise Provided For; Handling, Transporting, Testing or Inspecting Aircraft Components, Not Otherwise Provided for.	5171

*"Search Patent Classification Systems", the United States Patent and Trademark Office,https://www.uspto.gov/web/patents/classification/search.html [Accessed on July 14, 2020].

Following the determination of the top 10 CPC codes related to the UAV technology, in order to investigate the development of these top 10 patent codes, a new search was conducted on May 02, 2018, by examining 10 CPC codes separately in the USPTO database. As a result of the search, the total number of the patents related to these 10 CPC codes, which have been published between 1790-2018, is tabulated in Table 2.

IPC codes related to military technology in the field of weapons and ammunition for example are given in Table 3 and Table 4.

3.3 Hierarchical S-Curves

In this section, the technology life cycles of the CPC codes, which are obtained in the previous section, are generated using the logistics growth model. S-Curves related to the top 10 CPC codes of the UAV technology are shown in Fig. 7. To reveal detailed information on these S-curves, values of statistics of S-Curves related to the top 10 CPC codes of UAV technology are presented in Table 5.

Technology development stages are given in Table 6. As can be seen from Table 6, the TMR of the B64C code is computed to be nearly 88% using Equation (2). This means that future development will account for about 12% of the total development of the B64C code. The total number of patents corresponding to the B64C code is 33062 (see Table 2). The PPA of the B64C code in Table 6 is 4490, which is lower than the patent registration in the past (33062). *Yoon et al.* (2014) underscored that if the total number of patent registrations in the future is expected to be higher than the patent registrations

Table 3. International patent classification (IPC codes F41 and F42)[59,60]

IPC	Description
F41	Weapons
F41A	Functional features or details common to both small arms and ordnance
F41B	Weapons for projecting missiles without use of explosive or combustible propellant charge; weapons not otherwise provided for
F41C	Small arms; accessories therefor
F41F	Apparatus for launching projectiles or missiles from barrels; launchers for rockets or torpedoes; harpoon guns
F41G	Weapon sights; aiming
F41H	Armour; armoured turrets; armoured or armed vehicles; means of attack or defence
F41J	Targets; target ranges; bullet catchers
F42	Ammunition; blasting
F42B	Explosive charges, fireworks; ammunition
F42C	Ammunition fuses
F42D	Blasting

Table 4. Other military technologies and IPC codes[59,60]

- Travelling or camp articles specially adapted for military purposes: A45F 3/06
- Toy figures with self-moving parts able to perform military exercises: A63H 13/08
- Chemical warfare substances: A62D 101/02
- Warfare at sea (offensive or defensive arrangements on water-borne vessels, mine- laying, mine sweeping, submarines): B63G
- Warfare in the air (arrangement of military equipment, e.g. armaments, armament accessories or military shielding, in aircraft; adaptations of armament mountings for aircraft: B64D 7/00; other equipment for fitting in or to aircraft the articles being explosive, e.g. bombs B64D 1/04; bomb releasing; bomb doors B64D 1/06)
- Buildings, groups of buildings, or shelters, adapted to withstand or provide protection against, abnormal external influences, e.g. war-like action against air-raid or other war- like actions: E04H 9/04
- Doors, windows or like closures for special purposes; for protection against air-raid or other war-like action, etc.: E06B 5/10

Table 5. Values of statistics for S-Curves related to the top 10 CPC codes of the UAV technology

CPC	d	K	tm	r	R^2	1%	10%	50%	90%	99%
B64C	18280	37552	2012	0.108	0.950	1969	1990	2012	2033	2054
G05D	21738	65168	2013	0.107	0.914	1970	1992	2013	2035	2056
G08G	2015	57779	2026	0.130	0.995	1990	2008	2026	2044	2061
B64D	9215	30930	2014	0.108	0.966	1972	1993	2014	2036	2057
G01S	13490	84993	2013	0.108	0.976	1970	1991	2013	2034	2056
G06T	116	302799	2026	0.130	0.992	1990	2008	2026	2043	2061
H04W	542	546170	2022	0.203	0.993	2000	2011	2022	2034	2045
H04N	14379	779735	2025	0.109	0.993	1983	2004	2025	2047	2068
G06K	7779	311535	2026	0.110	0.996	1984	2005	2026	2047	2068
B64F	2024	6854	2014	0.108	0.978	1972	1993	2014	2036	2057
Average	*8957*	*144372*	*2019*	*0.109*						

d: initially the default amount of patents; K: saturation capacity (level); tm: time in which the logistics growth curve reaches half of its curve (middle time parameter); r: the logistic growth rate or steepness of the curve; R^2: the goodness of fit.

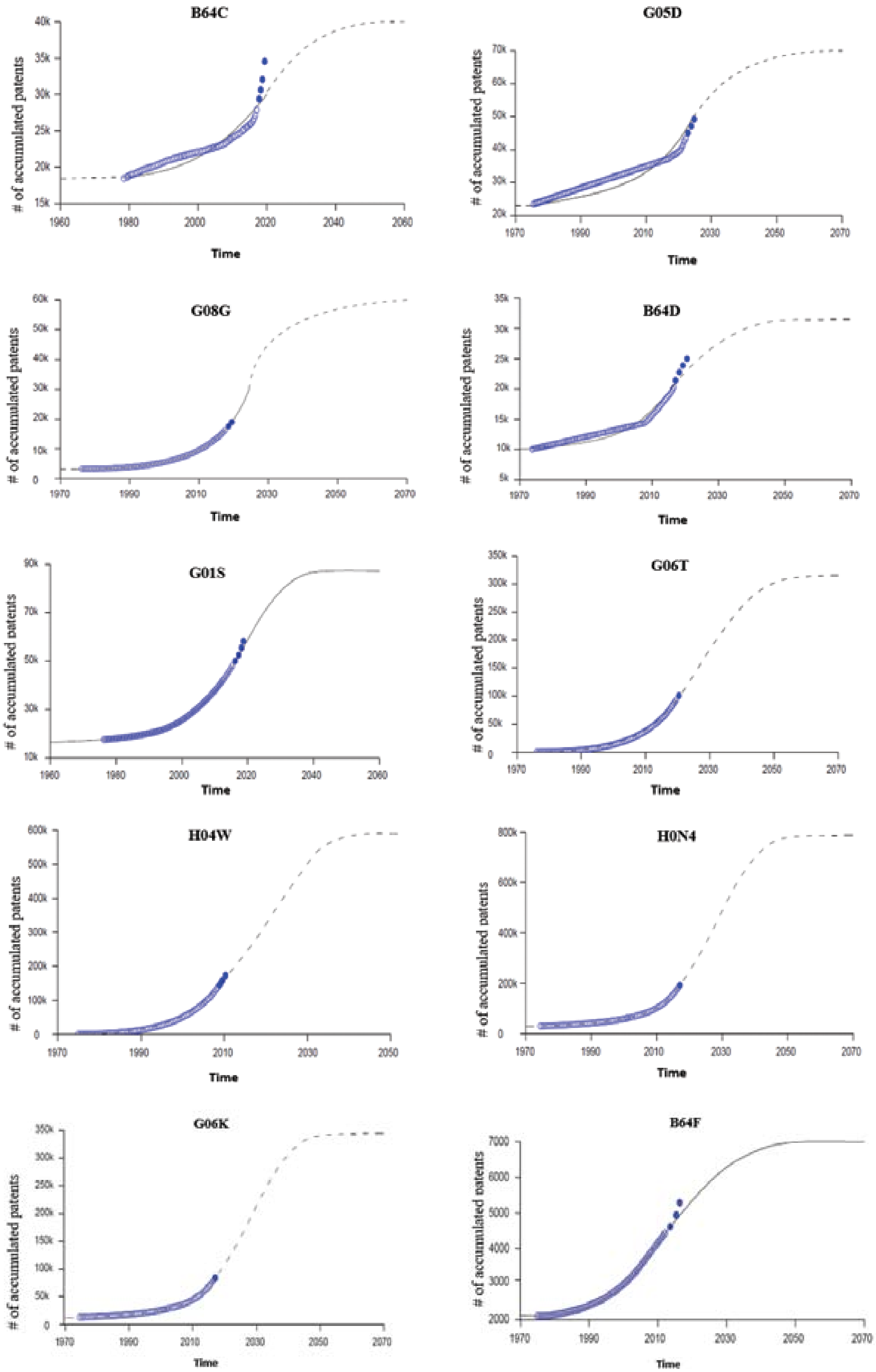

Figure 7. S-Curves related to the top 10 CPC codes of UAV technology.

Table 6. Life cycle stages of the top 10 CPC codes of UAV technology

CPC Code	The TMR (%)	The PPA	The ERL (k=0.9)	Life cycle stage
B64C	88	4490	15	Maturity
G05D	70	18961	17	Maturity
G08G	28	41535	26	Growth
B64D	76	7237	18	Maturity
G01S	71	24158	16	Maturity
G06T	25	226420	25	Growth
H04W	26	403251	16	Growth
H04N	30	541698	29	Growth
G06K	30	218540	29	Growth
B64F	75	1683	18	Maturity

in the past, this indicates that the intellectual property output of R&D will be less active in the future than it has been in the past. Hence, it is forecasted that the future intellectual property output of R&D related to B64C will be less dynamic in the future than it has been in the past.

As can be seen from Table 6, among top-ten CPC Codes, HO4W, G08G, G06T, H04N, and G06K are at the growth stage, indicating that these technology sub-domains still have substantial development potential. Here, the H04W CPC code describes the sub-technology of "wireless communication networks". Hence, this result is in line with the recent intensification of UAV R&D studies on the production of UAVs with swarm intelligence. As remarked in Unmanned Systems Integrated Roadmap 2017-2042 published by the U.S. Department of Defense[58], future warfare will be built on the swarming capabilities of UAVs. In this document, the battlefield is envisaged as where heterogeneous swarms of UAS directly support soldiers on the ground through ISR (Intelligence, surveillance, and reconnaissance) or aerial attacks. Therefore, it can be considered that warfare UAVs will be the backbone of armies in future. Additionally, it will be indispensable that forces and systems will be able to communicate between multiple levels of command among various units, share information and missions, and support mission leadership and chain of command as events unfold in real-time on the battleground in the future combat environment. In brief, this can be achieved through an enhanced communication network with cutting-edge technology. Thus, all these above-mentioned arguments verify the findings of our study in terms of the development course of the H04W CPC code, namely "wireless communication networks".

The advantages of the use of hierarchical S-curve method are summarised as follows:

- The relationship between UAV technologies could be defined hierarchically.
- Not only the target technology but also the related sub-technology could be evaluated.
- Technology forecasting of sub-technologies could also be taken into account in the forecasting of UAV technologies.
- A more robust and integrated UAV technology evaluation could be made.

The change in the design of the main system during the development of a technological product depends on the change in the sub-systems. Thus, the life cycle of the main system is linked to the life cycle of its subsystems[3]. The average value of the parameters that are required to apply Equation (1) is obtained from Table 5. To determine the technological development stages of the UAV technology based on the top 10 CPC codes, the following calculations are conducted according to the logistics growth model. In the following calculations, the development stages of the UAV technology have been determined. So that, the results obtained in sub-section 3.2. have been cross-checked based on the logistics growth model.

For K $_{(99\%)}$

$$Y(t)=\frac{K-d}{1+e^{-r(t-t_m)}}+d\,,\quad d=8957\,,\quad K=144372\,,$$

$$r=0.109 \text{ and } t_{(m)}=2019\,;$$

$$K_{(\%99)}\Rightarrow Y(t)=\frac{144372-8957}{1+e^{-0.109(t-2019)}}+8957=142928\Rightarrow\frac{135415}{133971}=1+e^{-0.109(t-2019)}$$

$$1.01=1+e^{-0.109(t-2019)}\Rightarrow Let x=0.109(t-2019), 0.01=e^{-x}\,, \quad (7)$$

$$\frac{1}{e^x}=0.01\Rightarrow e^x=100\Rightarrow x=\log_e 100=2.4342\,,$$

$$0.109(t-2019)=2.4342\Rightarrow(t-2019)=22.33\Rightarrow t=2041\left(K_{(99\%)}\right)$$

In equation (7), **K $_{(99\%)}$** represents the 99% saturation level for patents granted in UAV technologies. Based on this result, it is considered that by 2041, the UAV technology will have entered the saturation stage, as its saturation level will have reached %99 of its development capacity.

For K $_{(90\%)}$

$$K_{(90\%)}\Rightarrow Y(t)=\frac{144372-8957}{1+e^{-0.109(t-2019)}}+8957=129934\Rightarrow\frac{135415}{120977}=1+e^{-0.109(t-2019)}$$

$$1.119=1+e^{-0.109(t-2019)}\Rightarrow Let x=0.109(t-2019), 0.119=e^{-x}\,, \quad (8)$$

$$\frac{1}{e^x}=0.119\Rightarrow e^x=8.4\Rightarrow x=\log_e 8.4=1.35\,,$$

$$0.109(t-2019)=1.35\Rightarrow(t-2019)=12.38\Rightarrow t=2031\left(K_{(90\%)}\right)$$

According to the calculations in the equation (8), it is forecasted that the technology will be at the end of its maturation stage by 2031, since the technology has a K value of %90.

For K $_{(75\%)}$

$$K_{(75\%)}\Rightarrow Y(t)=\frac{144372-8957}{1+e^{-0.109(t-2019)}}+8957=108279\Rightarrow\frac{135415}{108279}=1+e^{-0.109(t-2019)}$$

$$1.25=1+e^{-0.109(t-2019)}\Rightarrow Let x=0.109(t-2019), 0.25=e^{-x}\,, \quad (9)$$

$$\frac{1}{e^x}=0.25\Rightarrow e^x=4\Rightarrow x=\log_e 4=1.35\,,$$

$$0.109(t-2019)=1.036\Rightarrow(t-2019)=9.5\Rightarrow t=2028\left(K_{(75\%)}\right)$$

Based on the obtained results, it can be interpreted that the technology will be in the middle of its maturation stage by 2028.

For K $_{(25\%)}$

$$K_{(25\%)} \Rightarrow Y(t) = \frac{144372 - 8957}{1 + e^{-0.109(t-2019)}} + 8957 = 36093 \Rightarrow \frac{135415}{27136} = 1 + e^{-0.109(t-2019)}$$

$$4.99 = 1 + e^{-0.109(t-2019)} \Rightarrow Let x = 0.109(t - 2019), 3.99 = e^{-x}, \quad (10)$$

$$\frac{1}{e^x} = 3.99 \Rightarrow e^x = 0.25 \Rightarrow x = \log_e 0.25 = -0.167,$$

$$0.109(t - 2019) = -0.167 \Rightarrow (t - 2019) = -1.53 \Rightarrow t = 2017(K_{(25\%)})$$

Considering the result that is obtained from equation (10), it is seen that the technology is at the beginning of the growth stage in 2017, as the granted patents in the UAV technologies are at the 25% saturation level. Thus, it still has a growth potential of 75%. Moreover, it can be noticed that the year determined for the beginning of the growth stage is coherent with the results presented in Fig. 4. Hence, this finding verifies the aforementioned results determined via the logistics growth model method.

For K $_{(10\%)}$

$$K_{(10\%)} \Rightarrow Y(t) = \frac{144372 - 8957}{1 + e^{-0.109(t-2019)}} + 8957 = 14437 \Rightarrow \frac{135415}{5480} = 1 + e^{-0.109(t-2019)}$$

$$24.71 = 1 + e^{-0.109(t-2019)} \Rightarrow Let x = 0.109(t - 2019), 23.71 = e^{-x}, \quad (11)$$

$$\frac{1}{e^x} = 23.71 \Rightarrow e^x = 0.04 \Rightarrow x = \log_e 0.04 = -0.96,$$

$$0.109(t - 2019) = -0.96 \Rightarrow (t - 2019) = -8.8 \Rightarrow t = 2010(K_{(10\%)})$$

Based on the calculation in equation (11), it can be noticed that as of 2010, the technology was in the emerging stage.

Technological development stages of UAV technology based on the top 10 CPC codes are shown in Table 7. As shown in Table 7, UAV technology has entered the growth stage in 2017, and the UAV technology will reach the saturation point in 2041. Previous studies also support the results of our study. According to Unmanned Systems Integrated Roadmap 2017-2042 published by the U.S. Department of Defense[58], progress in unmanned systems technology has escalated over the past decade, and the predicted growth curve points out that unmanned systems will have been replaced by an emerging technology by 2041.

Additionally, Fig. 8 illustrates the hierarchical S-curves of the UAV technologies, based on the top 10 CPC codes.

Table 7. Technological development stages of the UAV Technology based on the top 10 CPC codes.

Completion rate of the technology life cycle (%)	Technology development stage	Year
10	Emerging stage	2010
25	The beginning of the growth stage	2017
50	The beginning of the maturity stage	2019
75	Middle of maturity stage	2028
90	End of maturity stage	2031
99	Saturation stage	2041

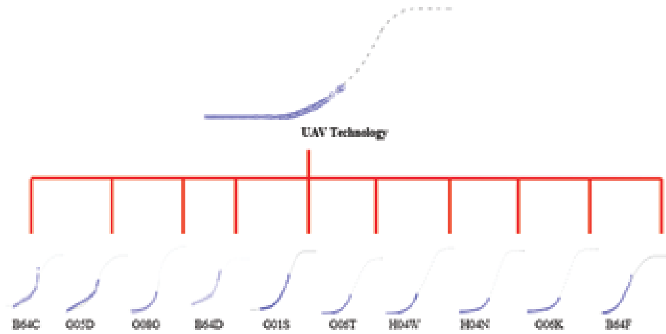

Figure 8. Technology forecasting of the UAV technologies with hierarchical S-curves.

4. CONCLUSION AND FUTURE STUDIES

UAV technology is one of the leading technologies in the defence industry. Monitoring the development of this technology provides valuable information for decision-makers. In this study, hierarchical S-curves are generated for the technology forecasting of UAV technologies. Moreover, the technology development life cycle of the UAV technologies is evaluated using the three indexes namely, the TMR, the PPA, and the ERL.

It can be concluded that the UAV technology has completed merely 25.6% of its technological life cycle and is just at the beginning of the growth phase. Furthermore, UAV technology is expected to reach the saturation stage by 2048. It is forecasted that the UAV technology will be replaced by a novel technology after 2048. On the other hand, it should be noted that this novel technology would not be completely independent of the existing UAV technology. Given the developments that the UAV systems are becoming completely autonomous, particularly in recent years, it is considered that the UAV technologies will develop towards the unmanned systems that harness substantially from the autonomous and artificial intelligence technology of the maturation stage. Besides, it was found out that among the top 10 CPC codes in the field of UAV technology, CPC codes of G08G, G06T, H04W, H04N, and G06K are at the beginning of the growth stage. It can be suggested that future investments should not be allocated to these technology domains, since it is well-known that a technology, which is at the maturity stage or the end of growth stage, would be replaced by a novel emerging technology. The results demonstrate that it is appropriate to invest in the technologies related to CPC codes of G08G, G06T, H04W, H04N, and G06K. Furthermore, organisations operating in the field of UAV technology need to perform their R&D studies on the technologies vastly associated with these CPC codes.

The H04W CPC code defines the sub-technology of "wireless communication networks". Hence, this indicates that our finding is in line with the recent studies on UAVs, which concentrate on the development of the UAVs' artificial intelligence features. Given that in a dynamic military force consisting of manned and unmanned systems, the need for unmanned systems to communicate effectively with other unmanned systems, headquarters, and ground troops on the battlefield and share data with them gaining importance increasingly, much emphasis should be put on communication technologies. Therefore, it is a necessity for the defense industry firms to focus especially on this sub-technology domain in R&D studies and to give priority to directing limited financial resources to this sub-technology. Hitherto, H04N and G06K CPC codes have completed only 30% of their technology life cycle. The G06T CPC code was found to be the technology class that has the highest potential for development among the sub-technologies of the UAV technology.

Technologies belonging to the B64C, G05D, B64D, G01S, and B64F classes are at the maturation stage of their technological life cycle. Therefore, to conduct efficient long-term R&D studies, organisations operating in the field of UAV technology should take these sub-technology fields into consideration by analyzing the potential development of the substitute technologies. Moreover, it is suggested that infrastructures should be established in the R&D departments of companies operating in the defence industry to follow the patent analysis data; plus, professionals who will analyse and process the patent data should be employed and the processed patent data should be included in the decision-making processes. Thus, companies operating in this field will have the opportunity and ability to follow the technologies, which are rapidly changing in our age, with the most up-to-date developments. Furthermore, taking these data, which are produced in R&D departments, into consideration by the decision-making mechanisms of the companies will allow companies to gain a competitive advantage in the short and long term. This study was conducted based on the patent data. Therefore, potential inventions and dramatic breakthroughs that might occur in the UAV Technologies in the future are not assessed in this study. This is the main limitation of the research. Moreover, the data used in the study was limited to the patent documents that were obtained from the USPTO patent database. Besides, only the top 10 patent codes were evaluated in detail after forming the S-curve of the UAV technology, as they were considered more significant compared to the remaining patent codes. Hence, it is thought that it might be more effective to expand the scope of the study by analyzing in detail the patent CPC codes of remaining sub-technologies related to the UAV technology.

In future studies, the number of patents cited in target technologies can be taken into account to generate hierarchical S-curves as well. In addition to that, market share and dimensions can be integrated with the hierarchical S-curves. Other patent databases such as Espacenet and WIPO can be used to obtain and analyses more patent data. Finally, other technologies in the field of defence science such as ammunition and blasting technologies can be evaluated using hierarchical S-curves in the future studies.

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