EXAMINING THE SPACE VALUE CHAIN THROUGH THE LENS OF THE CIRCULAR ECONOMY

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INTRODUCTION

With the world driving toward net-zero carbon emission, the space sector plays a vital role in addressing climate change and sustainability issues [1]. For instance, satellite earth observation helps monitor natural resources and provides key data for forecasting air quality and carbon emissions; satellite navigation and communications help optimise and improve traffic management, contributing to an effective supply chain and reducing carbon emission. Besides employing space technologies as an enabler in other sectors for achieving sustainability, it is also essential to examine the sustainability agenda within the space sector. The European Space Agency (ESA) established the Clean Space initiative in 2012, which delivers a sustainable approach to managing space activities, aiming to minimise the environmental impact on Earth and in space [2].

Following the triple bottom line concept, it is also vital to explore social and economic sustainability apart from the environmental aspect [3]. The Circular Economy (CE) is a concept contributing to sustainability. Stemming from sustainable manufacturing, the CE was developed and pioneered by Ellen MacArthur Foundation in the UK [4]. The CE aims to eliminate waste and pollution by circulating products and materials at their highest value, which drives the efficient use of finite resources. As opposed to the "take, make, use and dispose" linear economy model, the CE champions the idea of 6Rs (Reduce, Reuse, Recycle, Recover, Remanufacture and Redesign) [5]. As a result, CE profoundly impacts the value chain in an organisation's business model. The value chain in the space sector consists of the upstream and downstream segments involving various actors (stakeholders) [6]. The upstream segment covers space manufacturing activities such as launching spacecraft and satellites, including research and development and manufacturing actors. The downstream segment comprises space applications such as activities using space data for offering products or services. New space organisations are actively addressing the environmental impact of launchers (with SpaceX in particular advancing reusable launch technologies) [7]. However, there is limited research investigating how the CE impacts the space value chain.

Industry 4.0 is seen as an enabler of achieving sustainability. In the space sector, it is intertwined with the Space 4.0 concept. Industry 4.0, also known as the Industrial Internet of Things, refers to the cyber-physical systems where physical and virtual worlds are merged and enabled by the advancement of sensor, network and data analytics technologies [8]. According to ESA, Space 4.0 revolutionises space activities by including more space actors from governmental to private sectors and encourages collaboration through information exchange [9]. Although these technological advancements have the potential to transform the value chain and contribute to developing sustainable business models, there is no cohesive view on how Industry 4.0 could serve as an enabler in a circular life cycle for sustainability purposes in the space sector [10]. Hence, this initial research aims to explore how the CE impacts the space value chain in the era of Space 4.0 for sustainability purposes.

This paper first discusses the related work such as space value chain, circular economy, Space 4.0 and Industry 4.0, followed by the research methodology, which involves the preliminary literature review approach. This paper presents the findings, which lead to a conceptual map suggesting the ontological relationship between the research themes. We then propose future research opportunities based on the conceptual map and summarise the paper with the subsequent phases of this research. This research intends to contribute to achieving sustainability by circular economy through studying the space value chain in the era of Space 4.0.

RELATED WORK

Circular Economy in the Space Industry

The CE approach aims to make better use of materials or resources through the 6Rs to minimise the energy use and environmental impact of resource extraction and processing [11]. As opposed to the linear economy, the CE promotes redesigning the product life cycle to minimise input and production waste [12]. Particularly with the recycling objectives, it could reduce the dependence on foreign countries for extracting raw materials, which causes a strong environmental impact [13]. The CE is initially rooted in manufacturing [14], and it has a wider impact on an organisation's business model and value chain, which leads to economic benefits [10]. Experiential learning, resilience, entrepreneurial mindset, and effective leadership are attributes that potentially contribute to the success of applying the CE in the space sector [15].

The space value chain consists of an upstream segment (manufacturing) and downstream space activities (application) [6]. According to the UK National Space Strategy [16], there are six key segments in the space value chain: space manufacturing (design, develop and manufacture payload, platform and exploration craft), launch manufacturing and services (design, develop and manufacture launch vehicles rockets, manage the launches such as the spaceports and market the service such as ride-sharing), ground segment manufacturing and services (design, develop and manufacture ground systems and equipment such as end-user terminals, gateways and antennas, integrate third-party hardware and software and provide teleport services to consolidate signal and connect spacecraft to the internet), space operations (provide satellite capacity to services providers and manage in-space activities), space services and applications (provide data analytics services to end-users), and ancillary services (provide professional services in enabling the other five segments, such as insurance, finance, IT, market research and policy making). The entire commercial space economy is more than $350B, and the space-based economy is data-driven [17].

The CE is a recognised approach to promote sustainability [18]. It leads to sustainable development by promoting sustainable consumption and steering public and private investments [11]. The space sector could contribute to the 17 sustainable development goals (SDG) [19], where technology is essential in enabling this purpose. For instance, earth observation data could be used for achieving SDG 12 responsible consumption and production by optimising supply chain management, logistics management and energy management in production. Moreover, ESA's Clean Space initiative notably highlights three lines of action, *Eco-design*, *Cleansat* and *Active Debris Removal* [20]. The *Eco-design* initiative seeks to understand the product life cycle from the design phase to their end of life. It applies life cycle assessment for examining the environmental impact of launch vehicles and the environmental footprint left by the satellites and ground segments. *Cleansat* focuses more on applying the required technologies in complying with space debris mitigation requirements, and *Active Debris* Removal aims to remove satellites reaching their end-of-life from the protected regions, either re-entry or to a graveyard orbit. Therefore, CE aligns well with the Eco-design initiative in ESA. However, the CE implementation in the space industry remains nascent.

Space 4.0 and Industry 4.0

According to ESA, Space 4.0 "represents the evolution of the space sector into a new era, characterised by a new playing field [21]. This era is unfolding through interaction between governments, private sector, society and politics." In this era, we are seeing an increase in the number of countries and commercial actors involved in space, the move towards easier access to space, and the increased importance of space to the economy and well-being of citizens. The demarcation of space with 'non-space' players has become more opaque as more companies look to derive value from the data and services available from space. In "integrated applications" companies are seeking to create value through the combination of space data and services with terrestrial ones to deliver solutions to their customers. This has seen a shift in emphasis from technology push to market pull. The Size & Health of the UK Space Industry 2020 identifying space applications as one of the key areas of growth [22].

Along with the benefits of this new space age come some challenges. The volume of data created by new missions has grown significantly, leading agencies such as ESA to adopt cloud solutions. It is often no longer practical for end users to download entire datasets; instead data processing algorithms are often uploaded to the cloud where the data is stored leading to new collaborations. As reported in ENPNewswire, Airbus, Orange and Capgemini created a new platform for exploiting EO data as part of the Copernicus Data and Information Access Service (DIAS) [23]. However, there are numerous threats to space missions which can be directed at the ground segment, the space to ground communications and directly against the space segment [24]. The proliferation and value of new space missions now make them an attractive target. In 2021 the UK Government published its guidance on cyber security for space assets recognising the increasing risk and the need to improve awareness within the sector [25]. The increased space exploration activities in the new space age pose sustainability issues such as space debris and the potential impact of increased launches on the atmosphere [10]. For instance, UK Space Agency (UKSA) reports approximately 330 million pieces of space debris with 36,500 objects bigger than 10 cm, such as old satellites, spent rocket bodies, and tools dropped by astronauts orbiting the Earth [26]. Therefore, international cooperation is much more required than before, not only to achieve economic benefits but also to promote political sustainability [27].

Space 4.0 is driven by Industry 4.0 where technologies are adopted to enable efficient delivery of the space value chain activities [28]. The German government first coined the term Industry 4.0 at the Hannover Fair in 2011, which refers to applying technology to increase manufacturing competitiveness [29]. Some refer to it as Industrial Internet Things, which is seen as a cyber-physical system where physical and virtual worlds are merged with the advancement of sensors, networks and data analytics technologies [8]. Industry 4.0 has enabled more actors from smaller nations to participate in space activities by providing cheaper access, such as small satellite development [9]. Existing research in other sectors has identified nine specific technologies in Industry 4.0 [30]: big data analytics, autonomous robots, simulation, horizontal and vertical system integration, internet of things, cybersecurity, cloud computing, additive manufacturing, and augmented reality. Industry 4.0 is widely applied in the space sector, where it is used at a product or component level [10]. For instance, autonomous robots are employed to perform in-orbit assembly and augmented reality is used to facilitate new visualisation of space vehicles design and analysis.

RESEARCH METHODOLOGY

This research adopts the literature review method from [31] which consists of four stages as shown in Fig. 1.

Stage 1: Identification of research

Considering this is emerging research, we adopted GoogleScholar as the main academic database as GoogleScholar is one of the largest systems providing scholarly information [32]. Google Scholar was chosen primarily because it incorporates well-known academic databases such as Emerald and Elsevier. As a result, we retrieved a total of 198 papers. For the literature research, we applied search strings with the related keywords shown in Fig. 1 to return results found anywhere in the scholarly articles published to date. The keywords were chosen based on the research aim to explore how CE impacts the space value chain. We included keywords such as Space 4.0 and Industry 4.0. Technologies under the umbrella of Industry 4.0 are key enablers in the circular value chain, which fits well in the Space 4.0 context [33]. As a result, we retrieved a total of 198 papers.

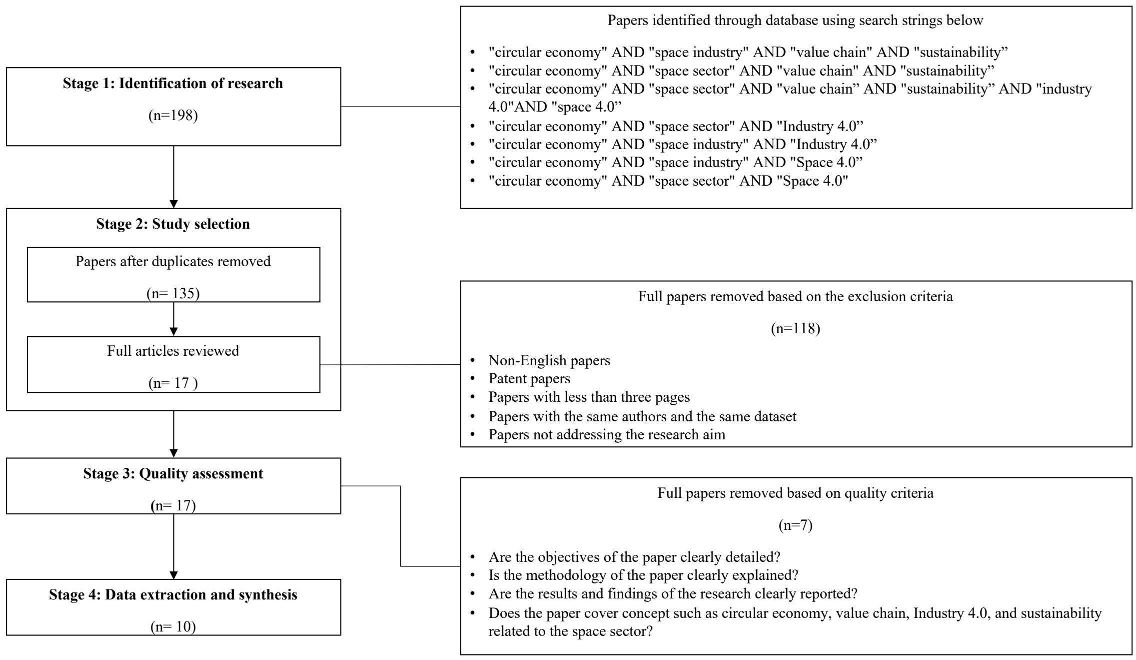

Fig. 1. Review strategy

Stage 2: Study selection

After removing the duplicated papers, a total of 135 papers remained. The exclusion criteria, shown in Fig. 1, were then applied when reviewing the papers. We found that most papers do not address the research aim, or the concepts were fragmented and did not provide a cohesive view of how CE affects or impacts the value chain in the space sector. Seventeen papers remained after this stage.

Stage 3: Quality assessment

To ensure the suitability of each paper to the research aim, we conducted the quality assessment based on the criteria shown in Fig. 1. We scored each source with 0 for not fitting, 0.5 for fitting partially, and 1 for fitting entirely, against the quality criteria, as in [31]. Then, using the heuristics principles suggested by [34], we excluded seven papers with a total score of less than 3.5. We then analysed the ten remaining papers in the next stage.

Stage 4: Data extraction and synthesis

We conducted a thematic analysis on the ten papers based on [35], which involved identifying and systematically documenting the derived themes. We then employed thematic ontology as in [36] to describe the relationship between themes, contributing to a conceptual map that sets the foundation for the next phase of this research, which we discuss further in the next section.

FINDINGS AND DISCUSSIONS

Overview of the selected papers

Apart from two reports, all the papers come from academic sources such as journal publications, conference papers, book chapters and theses. 50% of the papers adopted the literature survey approach and mainly leaned towards qualitative discussions of the research findings.

Research themes

Value chain, *business model*, *sustainability*, *application*, and *Industry 4.0*, are the five themes of the impact of CE in the space value chain that were identified through the literature analysis. Table 1 shows the derived themes and their related descriptions.

Table 1. Research themes

Research themes	Descriptions	References
Value chain	Describes how the CE concept could apply in the value chain	[10, 14, 37-40]
Business model	Illustrates how CE impact the business model	[10, 40]
Sustainability	Explains the outcome of applying CE in the space value chain	[10, 40]
Application	Explains how the space value chain contributes to sustainability in non-space sectors	[11, 41-43]
Industry 4.0	Depicts the role of Industry 4.0 in enabling CE in the space value chain	[10, 14]

Value chain theme: This theme suggests that CE (i.e., the 6Rs) could be applied at the component level, whether it is in the upstream or downstream value chain [10]. For instance, Yáñez Díaz [37] explores methods of recycling the resources, which leads to recovering hydrogen-containing waste gas streams using separation and purification techniques. Remanufacturing and redesigning are business-as-usual in the space sector as the materials and component values are extremely high [38]. Ramírez-Márquez and Martín [39] propose reducing, reusing, and recycling the photovoltaic panels used to supply electricity to satellites and space stations. The reuse concept in space manufacturing is applicable, such as in the Space X reusable rockets [14]. Additionally, an interdisciplinary approach where a value chain assessment that considers business and management factors should be conducted when assessing the applicability of CE in various sectors, including the space sector [40].

Business model theme: This theme is related to the *value chain theme* by considering factors such as particularly in considering factors such as strategy and goal settings when implementing the CE model [10, 40]. According to Helm [40], it is essential to integrate sustainability goals when developing organisation strategies. In addition, organisation functions such as operation, management and finance should be included before applying CE in the value chain.

Sustainability theme: In this theme, the CE application in the space value chain contributes to achieving sustainability and is mostly referred to as sustainability on Earth [10, 40]. However, the 3Rs (reduce, reuse, and recycling) can also be applied to achieve space sustainability, for example, the "Falcon" rocket developed by SpaceX [40]. This rocket is reusable and successfully launched "payloads" into space to transport cargo to the International Space Station. It is a significant advancement because no previous organisation had ever successfully landed and reused a spent rocket stage. This case study helps to reinforce the 3Rs as a source of competitive advantage for space logistics. Therefore, retrieving space debris and applying the 3Rs to produce a new reusable space product will help achieve sustainability in space. X and Y also subscribe to [3]'s triple bottom line principles in achieving social, environmental and economic sustainability goals.

Application theme: This theme refers to the outcome of the space value chain contributing to other non-space sectors. Argentiero and Falcone [11] applied data collected from the Earth Observation Satellite (e.g., solar irradiance, wind speed, precipitation, climate conditions, geothermal data, and business parameters such as price and financial viability to design software that helps make decisions on future clean energy initiatives. Similarly, the satellite data help to inform better forecasting of environmental conditions, which is important for climate change adaptation and unleashing the business potential for Finnish companies [42]. Data collected from the Galileo project contributes to creating digital Earth and CE [41]. It helps to boost the energy economy corridor for sustainable development. Copernicus provides satellite data for supporting the CE initiatives by developing resource-efficient, sustainable and integrated future factories.

Industry 4.0 theme: This theme suggests that Industry 4.0 have great potential in enabling CE implementation in the space sector. For instance, technologies such as big data analytics, additive manufacturing and autonomous robots could enable the implementation of CE by *reducing* material costs and production times while making the development of smart systems possible [14]. In addition, the space sector could learn from other sectors how to make the best use of these innovative technologies.

Literature gap

Based on the literature findings, the application of CE in the space sector is limited. The literature analysis shows that CE is mainly applied at the component level rather than at the holistic level. For instance, CE is employed in manufacturing a specific component or material used in a space mission, which is one activity in the value chain rather than the entire value chain. Therefore, we address this gap by adding the related literature from other disciplines, such as information systems, business and management, also from the non-space sectors.

When examining the space value chain through the lens of CE, it is essential to explore a circular or sustainable business model. A circular business model (CBM) refers to a business model where the conceptual logic for value creation is based on utilising economic value retained in products after use in the production of new offerings [44]. It is sometimes referred to as a closed-loop supply chain, which involves recycling, remanufacturing, reusing or one of the CE activities such as recovering, reducing or redesigning. Furthermore, CBM focuses on avoiding removing raw materials from nature [45]. The idea is to narrow, slow or close down the loops to retain economic value for as long as possible while delivering value to customers at the same time. CBM typically consists of attributes such as promoting “from cradle to cradle” logic, lengthening the lifecycle of products, sharing materials between organisations, encouraging the use of bio-based fuels and renewable energy sources, and exploring ways of managing waste as a new resource rather than implying additional costs for the companies [46]. Joyce and Paquin [47] propose a sustainable business model (SBM) by adapting the business model canvas from [48], and integrating it with the triple bottom line sustainability aspects (economic, environmental and social) as in Fig. 2.

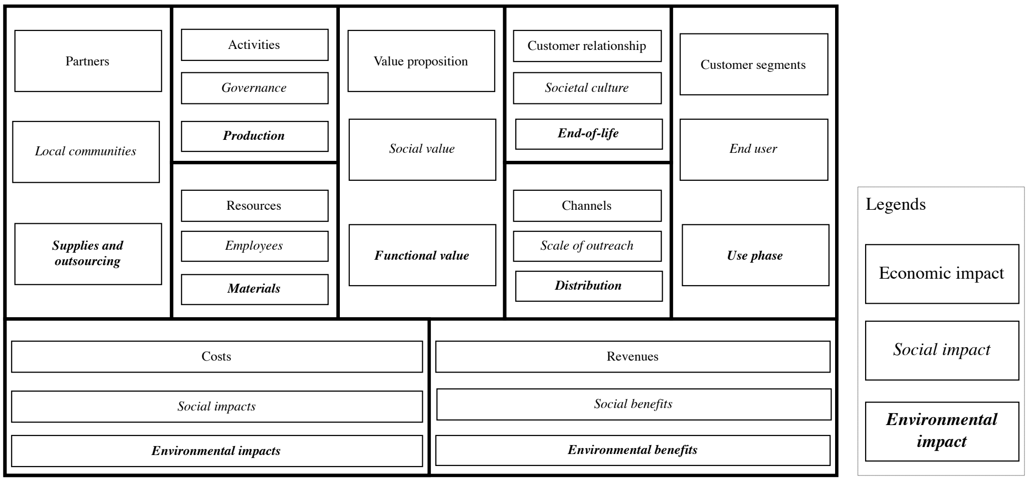

Fig. 2. Sustainable business model (adapted from [47])

The economic aspect fully adopts the original business model canvas, which could impact either the upstream or downstream value chain. In comparison, the environmental aspect examines the impact of the life cycle of a product or service, which we believe mainly involves the upstream value chain. The social aspect applies the stakeholder management approach (e.g., internal and external stakeholders) in assessing the social impact, which involves the downstream value chain. Industry 4.0 is vital in enabling CBM and SBM, mainly through data analytics [18, 33]. These business models involve vertical and horizontal integration, which generate huge volumes of data across the entire supply chain and product life cycles, including production and product usage [49]. In addition, the use of artificial intelligence, 3D printing, internet of things has been adopted by organisations to boost CBM and increase productivity [18].

Conceptual map of examining circular economy in space value chain

Based on the additional literature on CBM, SBM and Industry 4.0, Fig. 3 shows the holistic view of how CE impacts the space value chain. Based on the additional literature on CBM, SBM and Industry 4.0, Fig. 3 shows the holistic view of

how CE impacts the space value chain. The CE approach could impact mainly the upstream segment of the space value chain, such as the manufacturing of spacecraft, launch and ground segment equipment. The application theme refers to the downstream segment, particularly the space services and applications, where more focus is on the use of data collected in achieving sustainability purposes. From an organisation perspective, the CE application will impact the business model to achieve sustainability. As shown in Fig. 2, the sustainable business model could be applied in this context. As for Industry 4.0, the technologies will serve as an enabler in any segments in the space value chain. In the CE context, Industry 4.0 could improve the operational and production processes such as applying autonomous systems, the internet of things, and horizontal and vertical integration systems. This approach will lead to profound environmental effects by efficiently managing resources and reducing energy consumption and pollution production. Especially with the big data and data analytics technology also helps in measuring the economic, social and environmental impact of space manufacturing.

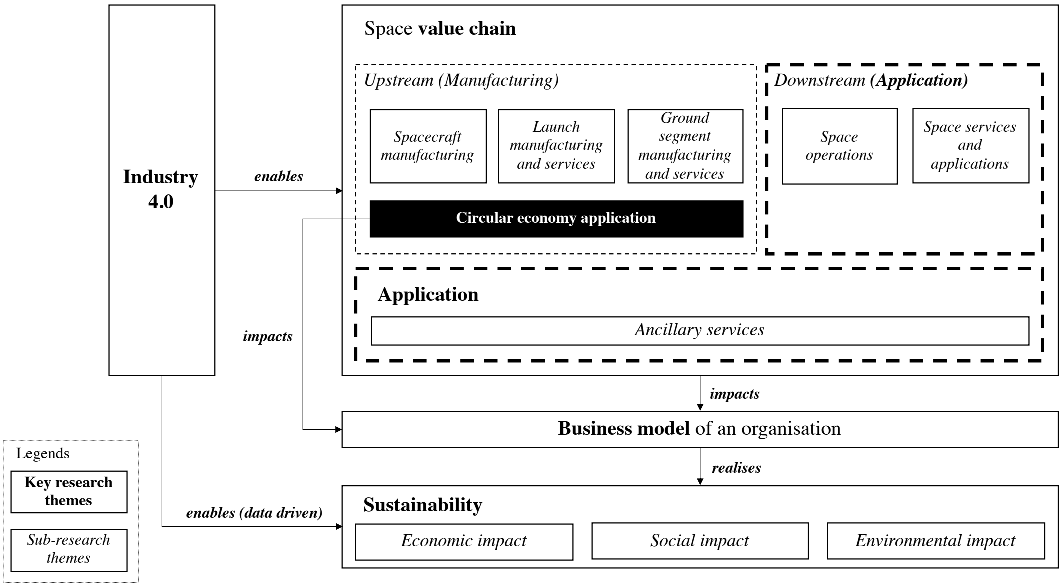

Fig. 3. The CE application in the space value chain

CONCLUSION AND FUTURE RESEARCH AVENUES

This paper has conducted a preliminary literature review for examining the space value chain through the lens of the CE. This research has contributed to the research gap where there is limited research on applying the CE in the space industry by proposing a conceptual map by analysing the existing literature that informs the future research avenues for either academics or practitioners as below.

Application of the CE principles

We conclude that CE's 6Rs (Reduce, Reuse, Recycle, Recover, Remanufacture and Redesign) apply to the upstream segment. Further research could incorporate life cycle assessment (LCA). LCA is a formal approach to measuring a product's or service's environmental impact by using indicators such as CO2 emission over the full cycle of a product or service such as raw materials extraction, manufacturing, distribution, use and end-of-life management [47]. Apart from identifying the environmental hotspots along a space organisation's supply chain of its products, LCA also helps reinforce the knowledge of upstream and downstream activities [50]. In addition, scholars and researchers could further explore design principles such as adaptable design [51] and design science [52] in the context of eco-design.

Application of Industry 4.0 in the CE environment

The existing literature suggests that Industry 4.0 is applicable in the CE implementation. Future research could examine how the technology enables the CE implementation by producing the relevant use cases. For instance, in what way could data analytics be used to inform the decision making, use or extraction of materials, improving the design and manufacturing process, and managing the waste.

Metrics for sustainable or circular business model

As shown in Fig. 2, the SBM aims to assess the sustainable impact from the economic, environmental and social perspectives. Further research could include developing the metrics for each component in the SBM. The metrics could inform certain decisions, such as whether a reusable launch is good for the environment or used for developing a mechanism for weighing the environmental impact of launches against the social and economic benefits. There is also an opportunity to explore how the Space Sustainability Rating (SSR) developed by the World Economic Forum Global Future Council on Space could be integrated into the metrics (e.g., the Data Sharing and Application of Design and Operation Standards modules) [53]. In addition, the UK Government has recently announced its intention to develop simple and accurate metrics for measuring the sustainability of space activities [54]. Moreover, this also prompts further research exploring the role of Industry 4.0 for this purpose.

The next phase of this research will involve a systematic literature review to expand this conceptual map by extending the literature search to other disciplines and sectors, considering this area is still in its infancy in the space industry. Moreover, expert interviews will be conducted to evaluate the feasibility of the themes in assessing the level of Industry 4.0 adoption and expanding the granularity of Industry 4.0 in enabling this circular approach in space manufacturing activities. The results will lead to developing a sustainability framework. Case studies will be employed to evaluate the applicability of this framework, where space actors involved in the upstream segment will be selected. The results will inform the best practices in implementing a circular life cycle approach in managing space manufacturing activities, which creates new or optimises capabilities for all space organisations involved in that segment for achieving sustainability goals.

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