An Empirical Exploration of the Potential Benefits of Applying Big Data Analytics for Improved Space to Space Operations Management in the Satellite Industry

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Abstract

The adoption of Big Data has grown exponentially over the past 10 years. Similarly, technological improvements in the satellite industry is making space more accessible than ever. The data collected by satellites can be leveraged for a myriad of applications across a broad range of sectors for improving life on Earth, whether that is through better communication infrastructure or better understanding of factors influencing Earth such as climate change. The application of Big Data to satellites is a relatively new concept. Big Data for operations management has changed the way the world does business with improvements stemming from a better understanding of all associated factors influencing operations. However, in each case Big Data for satellite applications has been leveraged to influence operations strategy on Earth. This paper maps the development of Big Data for operations management in a space to space context. As such, the techniques capitalised on by operations management teams are explored and analysed for their appropriateness in terms of live monitoring, enhanced reliability, increased efficiency and empowering decision makers. Space debris is a growing problem and, as such, better deployment, maintenance and end of life strategies are a core focus heavily reliant on each of these operational management pillars. In order to minimise risk whilst maximising potential returns for satellite providers, a proactive approach to satellite operations management by leveraging Big Data must be adopted.
Keywords: Big Data, Satellites, Operation Management, SmallSats, Constellation, Debris, Space-to-Space, Live Monitoring

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Ces 10 dernières années, l’adoption du Big Data a crû de manière exponentielle. Dans le même temps, les améliorations technologiques dans l’industrie satellitaire ont permis de rendre l’Espace plus accessible que jamais. Les données collectées par les satellites peuvent être employées pour de nombreuses applications à travers une gamme de secteurs très diverse liée à l’amélioration de la vie sur Terre, allant des infrastructures de communication à la compréhension des facteurs influençant de grands phénomènes comme le changement climatique. L’application de la Big Data au monde spatial est un concept relativement novateur. La Big Data appliquée au management des opérations a changé la manière que le monde avait de commercer, impactant la perception des éléments influençant les opérations. Cependant, dans la plupart des cas, la Big Data liée au monde satellitaire a été utilisée pour créer de nouvelles opportunités opérationnelles sur Terre. Ce mémoire cartographie les possibilités de développement de la Big Data appliquées au management des opérations dans un contexte « Space-to-Space » (du Spatial pour le Spatial). Ainsi, les différentes techniques déjà employées par les équipes de management des opérations sont explorées et analysées en fonction de leur appropriabilité en termes de contrôle en temps réel, perfectionnement de la fiabilité, augmentation de l’efficacité et autonomisation des preneurs de décisions. Les débris spatiaux sont un problème de plus en plus préoccupant, ainsi de meilleurs déploiements, maintenances et stratégies de fin de vie représentent des axes principaux dépendants grandement de chacun de ces piliers du management des opérations. Afin de minimiser les risques tout en maximisant les potentiels retours sur intérêts pour les fournisseurs de satellites, une approche proactive pour le management des opérations dans l’industrie satellitaire mobilisant la Big Data doit être adoptée.

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Chapter 1 - Introduction

The emergence of industry 4.0 has seen an explosion in the generation of data. The ubiquity and sheer volume of data created on a daily basis is astonishing with over 90% of data in the world today being generated in just the last two years (IBM, 2017). In any one day, over 2.5 quintillion bytes of data are produced. The emergence of data science, Big Data and its applications has been instrumental in the emergence of this sector. Understanding Big Data, making informed decisions and engineering appropriate strategies based on the analysis of this data providing actionable insights is becoming necessary for competitive business in every sector. Data powered businesses have the power to anticipate change and react in an agile manner like never before (Sagiroglu & Sinanc, 2013). Data has the power to change the world, pinpoint inefficiencies and with understanding; ratify any discrepancies in business modelling (Keppel & Hickey, 2018).

Capitalising on data acquired is paramount in engineering strategies to maintain a competitive advantage in an ever-evolving marketplace. As such, the development of smart, built for purpose algorithms is becoming a necessity, not an option. Embracing this change and the potential benefits of adaptivity is essential in fuelling optimal business performance in the internet age (Raphan & Friedman, 2014).

Space has long been an object of collective human fascination. Advancements and innovation in technology is fuelling the commercialization of an industry that was once reserved for governments. The huge growth in the number of satellites for a myriad of applications over the past 10 years is testament to an imminent new space race (Bhattacherjee, et al., 2018). However, like any technology, satellites are prone to failure and, as such, appropriate countermeasures for the removal of such satellites are paramount in limiting space debris (Liou & Johnson, 2006). Space debris presents a significant risk for satellites in terms of both deployment and satellite longevity (Klinkrad, 2006).

The application of big data for component monitoring has seen much success with adoption of machine learning and artificial intelligence techniques taking centre stage in the analysis of physical systems for preventative maintenance and the adoption of proactive repair protocols to minimise downtime for such systems (Lee, Kao, & Yang, 2014). SKYWISE, a data platform developed and used by Airbus has seen great success in the analysis and prediction of failures (Neugebauer, 2018). The subsequent increase in safety and operational efficiency is imperative in the progression of such cyber-physical systems as a key differentiator in effective operations management (Zhou, Fu, & Yang, 2016).

The objective of this research project it to explore and analyse the benefits of big data analysis for the satellite industry. As big data applications such as component monitoring and predictive analysis techniques provide a viable solution to determining product lifespan, they will be explored in detail with extensive referencing of both appropriate academic and scientific articles made throughout this paper. Big Data in Space is a growing industry. However, to date much of the focus has been on applications of Big Data in Space to improve operations management on Earth. Implementing similar applications to the satellite industry for the satellite industry would be invaluable in optimising operational efficiency in a space to space context. Ensuring safety for satellites in orbit is yet another major concern in the industry both with regard to satellite failure due to internal component failure or external factors such as space debris (Kessler, Johnson, Liou, & Matney, 2010). As such, analysis of appropriate end of life techniques to reduce the risk of catastrophic collisions will also feature heavily in the development of appropriate strategies to optimize operational efficiency (Cornara, Beech, Belló-Mora, & Martinez de Aragon, 2010).

Chapter 2 - Big Data

Big data analytics and the value it can add are changing the way the world does business. The adoption of such technological change and digitalization across a myriad of industries is testament to the power of analytics with exponential growth in this business sector over the past decade (Gandomi & Haider, 2015; Ward & Barker, 2013; Chen, Chiang, & Storey, Business intelligence and analytics: from big data to big impact, 2012).

In order to better understand the value big data can create for a business, it is first necessary to understand, just what exactly is big data? Big data is a collective term used to describe large volumes of stored information. The application of analytical tools and models provide a means of exploiting and leveraging this data in order to glean invaluable insights. There are three primary branches of analytics which are employed by companies to answer the what, the why and the how. These three branches of analytics are descriptive, predictive and prescriptive. Descriptive analytics provides information on what has already happened and is the preliminary and often, most simple form of data analytics. Predictive analytics is the process of developing an understanding of a past event and why that event happened in order to anticipate the reoccurrence of a similar event. Finally, the most complex branch of analytics is prescriptive analysis which serves to provide information on how to make an event happen (Evans & Lindner, 2012).

2.1 CRISP-DM

The standard methodology adopted by business intelligence and data science experts is known as Cross-industry Standard Process for Data Mining or CRISP-DM, illustrated below *(Figure 1)*.

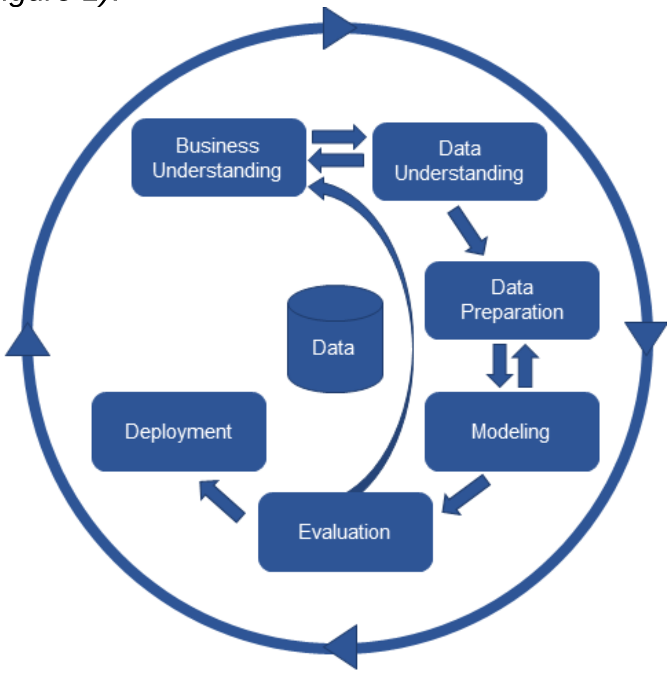

Figure 1: CRISP DM Methodology (Taylor, 2017)

The CRISP DM methodology serves as a road map for business intelligence experts in the development of analytical tools. The model consists of six differing functions, moving from business understanding to deployment of a project. In order to understand the potential impacts on strategy, each of these functions are detailed below (Chapman, et al., 2000).

2.1.1 Business Understanding:

The first step in understanding exactly what analytics are needed by a business is to understand project objectives and requirements from a business standpoint. Understanding requirements is essential in formulating and defining a problem and preliminary plan.

2.1.2 Data Understanding:

Understanding data is essential in the optimising both project efficiency and maximising project outcomes. This requires the exploration of available data to determine applicability and appropriateness to the business problem at hand.

2.1.3 Data Preparation:

This is the cleaning and construction of a new dataset containing all relevant and important data required to complete the project. So called “dirty” data is cleaned and irrelevant or unimportant data may be pretermitted in the interest of simplifying the problem.

2.1.4 Modelling:

The modelling of data refers to the application of appropriate analytical techniques in the development of systems to meet project specifications. These systems can vary from simple data mining techniques such as Classification and Regression Trees (CART) to more complex and sophisticated systems such as Neural Networks (NN).

2.1.5 Evaluation:

Evaluation of differing models is essential in ensuring a robust system which performs appropriately and meets the specifications of the business problem at hand. As such, this stage of activity is connected back to the business understanding stage. The evaluation stage also accounts for testing of the system to ensure models will perform well for the task at hand.

2.1.6 Deployment:

The penultimate step in the CRISP-DM methodology is the deployment of models in order to answer the original business question as outlined in the business understanding step. It is by this means that the development of analytical methods to provide insights based on collected data can add value to businesses in terms of better understanding; also known as business intelligence.

2.2 Business Intelligence

Business intelligence is a broad term encapsulating the technologies and methods employed by businesses for the effective analysis of data. However, it is the effective analysis of this data that fosters better decision making in the business environment. Technological advancements in the data industry are better equipping all organizations with the necessary tools to transform this knowledge into profit by answering the what, the why and the how (Liautaud & Hammond, 2000).

2.3 Big Data for Better Operations Strategy

Strategy is the employment of a plan designed to achieve a specific goal. Development and deployment of this plan requires the answering of three questions; what, why and how. Progress in the field of big data is quintessential in answering these questions more effectively and consequently, developing better strategic plans. After all, as Sir Francis Bacon once said, “knowledge is power” (Bacon, 1597). As such, the effective answering of these three questions is instrumental in the development of any effective business strategy (Porter, 1996). Quantitative analysis of data to reveal patterns, correlations and trends now comprises a significant portion of the decision-making process for business strategists in a myriad of management sectors. Big data is empowering decision makers to make better strategic choices based on the reassurance that are acting with full knowledge on all available data. However, for the purposes of this research, big data driving decisions in the operations management sector will be a key focus.

Operation management is the planning, controlling and directing of activities within a business to satisfy customer needs. This encompasses both the conversion of materials into good and work into services. The primary goal of this facet of management is to optimise processes and protocols in order to maximise revenue streams within an organisation whilst gaining a competitive advantage (Chase, Aquilano, & Jacobs, 2001).

The emergence of industry 4.0 and the subsequent explosion in data is providing operations strategists with all the tools to perform at the highest level. The generation of data from both IoT devices and cyber-physical systems has been instrumental in the emergence of new data sources resulting in an exponential increase in data volumes. Data is everywhere from GPS units to medical devices to machine sensors. However, without the effective application of the CRISP-DM, this raw can data rarely be leveraged to provide actionable information. Disregarding these data sources would impede strategy by relying on organisations to make decisions with only a portion of the information available to them. The CRISP-DM methodology provides the framework for transforming business problems to gain completive advantages through data. Leveraging this data alongside already available business data is ushering in a new era of decision making (Provost & Fawcett, 2013). Consequently, the interconnected and interdependent pillars of Big Data Analytics for operations management will be explored.

2.3.1 Live Monitoring

Availability of data in real time is changing the way we do business. Industry 4.0 and communication infrastructure is not only advantageous in the development of more appropriate strategic decisions for operations management. The live monitoring of end-to-end processes with visualisation tools is encouraging enterprises to adopt an increasingly agile approach to making these decisions. Real time alerts enable businesses to be proactive rather than reactive (Lou, Liu, Zhou, Wang, & Sun, 2012). This technology is more available then ever with visualization tools presenting data in an easily digestible format for effective communication to both the data savvy and business people alike (Chen, Chiang, & Storey, Business intelligence and analytics: from big data to big impact, 2012). Live monitoring of systems has also been very effective in optimizing product lifecycle management. Product lifecycle management is the task of managing the life of a project from its creation through development and manufacture to service and finally, end of life and disposal (Stark, 2015).

2.3.2 *Improving Efficiency*

Analysis of interdependent business processes multiple facets of business operations such as manufacturing and supply chain management among others. Identifying bottlenecks and operational inefficiencies is paramount in maintaining a competitive advantage (Lee, Kao, & Yang, 2014; Jin, Wah, Cheng, & Wang, 2015). Analysis of manufacturing processes in factories has given rise to the research in the field of smart factories; an adaptive, flexible manufacturing line that is designed to optimise efficiency. Tasks such as scheduling are automated which negates the possibility of deadlock resulting in maximised throughput (Wang, Wan, Zhang, Li, & Zhang, 2016). A somewhat abstract example of optimisation in the supply chain has been employed in delivery by UPS who almost never turn left (Berman, 2017). The science behind this strategic decision was developed by mathematician George Dantzig in 1969 who introduced the vehicle routing problem. However, though technology has developed exponentially, the principles of this optimisation problem are the same. The effective analysis of vehicle routing and traffic data results in increased delivery speeds while reducing fuel costs (Dantzig & Ramser, 1959). Caterpillar have employed analytical methods in order to improve efficiency also. Component analysis and travel data for Caterpillar marine and dump trucks has been leveraged in order to provide actionable insights into optimal machine configurations. This data was leveraged by decision makers to maximise efficiency for customers resulting in increased component lifetime, reduced fuel wastage and maximised maintenance intervals (Marr, 2017). Optimisation of efficiency in terms of operational throughput can maximise revenue whilst maximising customer loyalty and, as such, competitiveness and profitability (Griffin & Herres, 2002).

2.3.3 *Enhanced Reliability*

Efficiency and reliability are closely linked; however, reliability can be more detrimental externally in terms of customer loyalty and internally with regard to financial risk. Improving reliability is an important facet of operations management in an enterprise. Employing descriptive analytical methods to carry out root cause analysis is a bid to identify patterns and correlations is an important differentiator in maximising customer satisfaction and consequently, business performance (Lee, Kao, & Yang, 2014; Spiess, T'Joens, Dragnea, Spencer, & Philippart, 2014). Leveraging information learned from descriptive analysis is crucial in the development of accurate predictive analytics models. However, reliability metrics differ depending on factors such as business processes, sector and industry. As such, employing the CRISP-DM methodology to ensure business objectives are met is essential. SKYWISE a wholly owned subsidiary of Airbus is employing such analytical techniques for monitoring of components are predicting their failure (Airbus, Airbus - SKWISE, 2018). Airbus Flight Hour Services (FHS) operates in tandem with SKYWISE to schedule the maintenance and repair of aircraft. This service is minimising ground time for aircraft by scheduling maintenance at appropriate times and through the effective management of inventory to ensure replacement parts are where they need to be on time. This service is indicative of the power of analytics in enhanced strategic management of operations. The service is dedicated to increasing aircraft availability, optimising operations and maintenance and subsequently, maximising profit (Airbus, Airbus Flight Hour Services, 2018).

2.3.4 Empowering Decision Makers

Ambiguity was once a major hurdle in decision making for any member of the C-Suite. The application of big data analytics by organizations has made this a thing of the past. New data sources like social media for applications such as sentiment analysis to determine customer contentedness with a product or service are proving invaluable in the engineering of new strategies (Keppel & Hickey, 2018). Financial analytics models can be employed to determine risk and, as such, can be leveraged to mitigate that risk within organizations. Real time data is enabling businesses to be proactive an encouraging the adoption of agile methodologies in order to mitigate risk whilst maximising financial rewards. However better decision making in the upper management is just one of many benefits of capitalising on Big Data. The Big Data for Operations Management ecosystem is illustrated below *(Figure 2)* to demonstrate the formulation of such a business approach and the process through which better decisions are influenced (Khanna, 2016).

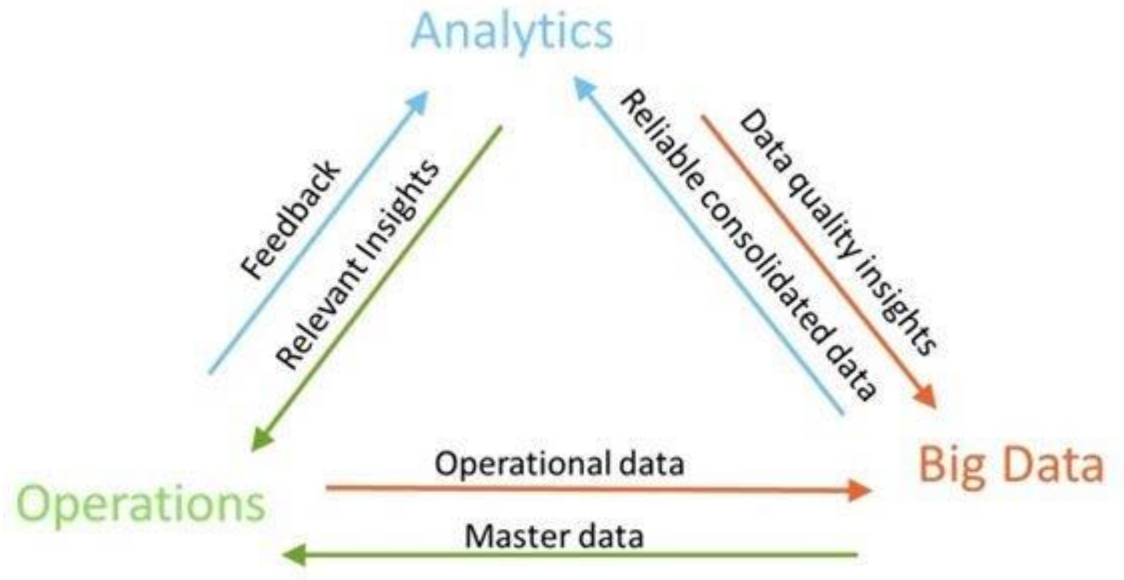

Figure 2: Big Data for Operations Management Ecosystem (Khanna, 2016)

Chapter 3 - Big Data in Space industry

3.1 Trends in Satellite Industry

This section will explore and analyse past and current business trends in the satellite industry. As the satellite industry is a broad term encapsulating radically different systems for a multitude of applications, three different satellite types will be investigated; SmallSats, Satellite Constellations and Satellites

3.1.1 SmallSats, a satellite market disruption?

The satellite industry was impeded by several aspects that slowed its development after years of dynamism linked to the Cold War, Technology and Internet development. Those are long development times, high barriers and low accessibility to Space, costly and risky investments and technical complexity of products and launches. Each of which can be attributed to the long quiet period without any major change or progress of this industry.

However, since the 1990s, a new trend altering this structure appeared with various new entrants launching new types of smaller and significantly cheaper satellites and still completing missions comparable to the ones only achieved by traditional industrial satellite providers once. This trend, exploiting the miniaturization linked to high-tech innovations and technologies, is characterized by a creation of new opportunities in satellites usage (dos Santos Paulino & Le Hir, 2016).

Those miniaturized satellites, called SmallSats, can replace large satellites for some specific uses, but can also challenge them. As an example, SmallSats can provide images with one-meter precision to imagery consumers, with a higher revisit rate and customizations depending on the task requested by customers compared to traditional satellites where this kind of adaptability is often prohibitive and, as such, may not fulfil these kind of operational needs (Johnson, Corcoran, & Rohrer, Platforms Designed for Big Data Provisioning with Small Satellite Constellations, 2017).

This shift in structure is also leading to an increase in the commercialization of space. Development of new products and services linked to specific and unique SmallSat applications are revitalizing the Low Earth Orbit industry. This is increasing accessibility to this industry and creating opportunities for businesses. The increase in interest and in popularity of this sector is reinforced by the reduction in cost and timescales which explain the relatively recent escalation in new satellite actors and growth in the number of launches (Lewis, et al., 2017). Still, Low Earth Orbit has some limits compared to Geostationary Earth Orbit, especially with regard to coverage and technological capabilities. As such, a specific and complex communication system is required to achieve an efficiency comparable to that of large satellites.

3.1.2 Constellations, a way to improve SmallSats efficiency?

To achieve persistent widespread or global coverage from LEO, it is necessary to construct Satellite constellations and a satellite-to-satellite-to-ground communication system composed of various similar satellites. This system will fulfil analogous tasks and missions designed to be in complementary orbits for a shared function with interoperability and a means of global system control (Wood, 2003).

This recent growing trend to develop large-scale satellite constellations with low-cost small satellites has brought the need for an efficient and scalable maintenance strategy decision plan as well as an efficient satellite constellation management plan (Jakob, Ho, Shimizu, & Yoshikawa, 2018; Cornara, Beech, Belló-

Mora, & Martinez de Aragon, 2010). However, there is some concern about the effectiveness of such launches and, as such, the existing space debris mitigation guidelines are relevant. Low Earth Orbit is offering a narrow orbital space that is threatened by the predicted intensification of traffic linked with constellations development (Wood, 2003).

Furthermore, there are also specific concerns about the real efficiency of such an organization, with cost, feasibility and timeline issues. The miniaturization, interchangeability and standardization of components give a cost advantage to SmallSats compared to larger satellites. These systems are also advantageous in their rapid time to market while enabling agile development (Johnson, Corcoran, & Rohrer, Platforms Designed for Big Data Provisioning with Small Satellite Constellations, 2017). However, a constellation of satellites is composed of multiple interconnected similar satellites which each require sufficient, incompressible build time. The development of such systems often has a total cost of over one million dollars. In the end, large constellations are more expensive than traditional satellites, which accentuates the importance of management and strategy in such a context; where actors are still analysing to what extent SmallSats are cheaper than GEO satellites (dos Santos Paulino & Le Hir, 2016).

3.1.3 GEO Satellite, towards specific uses and tasks

Large satellite platforms have an advantage in terms of their risk mitigation, capabilities, mission assurance and ability to handle demanding tasks. To date, large satellite platforms are considered favorable for defense and intelligence missions. This is especially true as they are more efficient for applications where small and specific region coverage is important, but also because GEO satellites allow more adaptability to technological changes than an entire constellation. This is so, as it is easier to replace one large satellite than numerous interdependent SmallSats (Johnson, Corcoran, & Rohrer, Platforms Designed for Big Data Provisioning with Small Satellite Constellations, 2017; Johnson S. , Platforms Designed for Big Data Provisioning with Small Satellite Constellations, 2016). GEO can also provide a way to mitigate congestion predictions in both LEO and GEO using hybrid multi-layered constellation networks. These hybrid networks are still challenged in assuring a high quality of service. One solution to be considered was developed by Nishayama et al. in 2011 which employed a congestion prediction-based traffic detouring method.

Major emerging trends in the Space sector are dynamizing business opportunities in the Satellite industry and making important changes in what was a previously quiet business environment. These changes in tandem with the intensification of development by Space actors, traffic and launches are creating new challenges for Space strategy with major concerns to operational, lifecycle and debris management. The application of big data for improving operational decisions has already proven fruitful in terrestrial applications with major adoption across all industries in the last 10 years (Chen, Chiang, & Storey, Business intelligence and analytics: from big data to big impact, 2012; Zhou, Fu, & Yang, 2016). As such, it is necessary to analyse where Big Data can be applied to these opportunities and challenges in the satellite industry to impact strategic decisions for operations.

3.2 How big data can interact with Space industry

Understanding the potential of employing Big Data to the space industry in the future requires the exploration of current applications and the manner in which Big Data has influenced those applications.

3.2.1 The satellites services market: New big data trends

Industry 4.0 and the proliferation of data and data ubiquity has focused engineering efforts on increased cosmic data collection, shrinking electronics and sensors, increased efficiency of satellite constellation management, and availability of flexible short-term/low cost missions. Not only Satellite Industry structure changed, but its market, one once traditionally subsidized by government agencies is now transitioning to an information-as service market where private actors are willing to invest in a service that will provide them with relevant information from Space for Earth applications (Johnson, Corcoran, & Rohrer, Platforms Designed for Big Data Provisioning with Small Satellite Constellations, 2017).

However, the increase in available data is creating a challenge in terms of determining the best methods in order to meet end customer needs. Data understanding is a major driving force in an increased demand, not just for voluminous data but for quality data enabling players to work smart, not hard (LaValle, Lesser, Shockley, Hopkins, & Kruschwitz, 2011). As such, the majority of those private or public customers aren't asking for more data, but for better information. This particular point is deeply connected with SmallSats as they have specific technical capabilities such as night vision, accuracy through clouds and bad weather, and, can provide rich information tailored to meet customer requirements. However, the increase in the variety of application specific satellites is inciting the need for better analytical models and tools to provide quality insights into collected data. This operational challenge is being taken up by Big data firms creating analytics services adaptable to customer's needs, for both simple and more complex applications.

Creating added-value services on ground in order to satisfy the increasing demand of application specific information has created an emerging market for new sectors adopting such technological systems. The benefit of such a problem-solver service lies in the ability to identify anomalies in data through automation as opposed to the labor-intensive traditional data analysis methods of yesterday. This has manifested in a promising future for such services in the satellite industry. Indeed, NSR and Euroconsult estimated that Big data analytics applied to the traditional Satellite data market could incorporate services with a value ranging from approximately $6B to $15.8B by including new markets associated with industry 4.0 (Edinger, 2017).

With such an estimated value, the early adoption of such services to meet the demands this operational challenge is creating is a major stake for Space-to-Earth service companies which is invoking a need for better strategic decision-making in a myriad of different Big Data applications in this sector.

3.3 Big data impacting Operations Strategy on Space-to-Earth sector

The development of SmallSats has acted as a catalyst and enabler in the emergence of Big Data for space, allowing access to more velocity, variety and volumes of data. Now, it's Big data that is creating new markets and helping an already existing market to meet demands in an industry where information is more and more important for Space-to-ground services segments. Exploring the benefits of employing such analytical techniques is paramount in understanding potential new applications. As such, it is first necessary to analyze the impact of such services on Operations Strategy in the Space-to-Earth sector. Several differing examples of applications will be explored in order to better understand the progression of this industry.

3.3.1 Remote sensing:

The traditional remote sensing market is already dependent on computer calculations. As Industry 4.0 progresses, the development of new innovative solutions to current challenges have shaped the direction of the market, with concern to cloud computing, IoT and high mobility. Big Data analytics methods have paved the way for the creation of new systems detailing descriptive, predictive and prescriptive information (Wang, Gunasekaran, Ngai, & Papadopoulos, 2016). Improved methods and technology can provide deep monitoring and forecasting of visualization systems, in line with the development of SmallSats which allow better revisit rates and more current data; a key resource in determining the appropriateness of differing computing models to identify patterns.

Between the collection of data, such as imagery, and the final user, a third actor offering value-added services by leveraging this Big Data is involved. This is creating a real impact on the strategic decision making process: The end user is now able to use information with access to complex scalable services to meet their needs without having to create costly structures to interpret data (Johnson, Corcoran, & Rohrer, Platforms Designed for Big Data Provisioning with Small Satellite Constellations, 2017). Scalability with regard to both data collection and interpretation is better equipping users with all the tools necessary to collect high-quality information at regular time intervals, sometimes from different sources. This progression in the space industry has enabled the LEO market to overtake the public sector's ability to meet a growing demand in analytics for markets such as agriculture, defense, earth observation and climate change.

3.3.2 Earth observation:

Traditionally, Earth Observation (EO) was a sector where significant investments were made in terms of machinery and justified with a large variety of technologies incorporated to ensure a wide range of applications were met by satellites.

However, "Big Data" services connected to this sector fell short due to limitations incurred in data collection where information was not current, reliable or qualitative enough to have a significant impact on the demanding On-ground markets, asking for more appropriate services.

Furthermore, the development of constellations, cloud computing and storage has alleviated this constraint by ensuring effective voluminous data collection is carried out in an efficient manner and subsequently can be leveraged to provide insights in a timely manner to the Earth Observation market. Big data is impacting operational strategy with new methods and process of automatization and prediction that create value for final users who are now changing they behavior towards how to manage Earth Observation data sets (Tyc, et al., 2017).

3.3.3 Agriculture:

The increased demand for smart machines and sensors for a myriad of different applications in the agricultural industry has been instrumental in the development of new smarter farming processes. As such, the industry is becoming increasingly data-driven. Technological advancements and increased accessibility to products and services such as IoT devices and cloud computing is fueling growth in this industry and empowering decision makers to optimize their business processes. This new and disruptive industry is known as Smart Farming (Sundmaeker, Verdouw, Wolfert, & Pérez Freire, 2016).

Precision Agriculture is the process of taking in-field variability into account when planning. Smart Farming on the other hand, goes beyond this by developing appropriate operational management strategies to increase reliability, improve efficiency and to empower decision makers to make better choices. Improving operations in this context is achieved by leveraging data dependent on factors such as situation, context and location in a live manner through real time monitoring; enabling a more agile approach to operations management in this sector (Wolfert, Sorensen, & Goense, A future internet collaboration platform for safe and healthy food from farm to fork, 2014). Real-time data collection is employed to enable agile responsiveness while minimizing risk. This is especially true in situations such as adverse weather conditions or disease alerts. The implementation of such smart systems to enable the agricultural industry to operate more efficiently relies heavily on existing technologies for applications such as component monitoring, operational data analysis and predictive analytics. Satellites can provide current and accurate data on factors such as climate which is also a major differentiator in effective farming.

The use of satellite imagery for farming has given rise to information as a service in this sector. Determining the best operational strategy for tasks which would have been traditionally carried out with much ambiguity is easier than ever. Information regarding the best strategy for long term planning and better information for a proactive approach to operational management is maximizing efficiency for all adopters. This manifests in applications such as best performance configurations and proactive maintenance of machinery, planned crop rotation and select crop choice based on meteorological data (Wolfert, Ge, Verdouw, & Bogaardt, 2017).

3.3.4 Climate change:

The effects of climate change are becoming more apparent by the day. Warmer climates are melting ice caps and changing the world as we know it. Unfortunately, along with increasingly destructive storms occurring as a byproduct of this change, diseases that were once restricted to warmer climates are now capable of spreading much farther than before (Rohr, et al., 2011). As such, Big Data analytics has played an important role in recent years in determining the probability of disease spread with regard to the changing climate. Employing anomaly detection algorithms to monitor and report change is enabling us to be more prepared than ever (Manogaran & Lopez, 2018).

One of the first scientific branches to employ space as a means of gaining better data as early as the 1960s. Today, space is utilized by governmental and private institutions for the monitoring of factors affecting climate such as the atmosphere and ocean. This data is then leveraged to provide better weather forecasting, warnings for storms and for monitoring the rate at which the climate is changing along with environmental activities. Today weather prediction models rely on approximately 75% of data collected in space (Faghmous & Kumar, 2014). The effective analysis of this data is paramount in determining the best strategy for operations; whether that means the efficient evacuation of an area prior to a storm or the inoculation of at-risk demographics due to disease spread.

Technological improvements are continually improving both the both the manner in which data is collected and the granularity of that data. This coincides with better modelling techniques which are resulting in increased accuracy. The growth in the number of satellites, the introduction of constellations and improved satellite components measuring a broader range of data are providing better coverage for climate change monitoring enabling data scientists to provide a fuller picture than ever before. Interoperability between satellites is also reducing downtime with new satellites replacing old or even complimenting already orbiting satellites.

A major obstacle in the birth of this new data collection is continuity. Redundant satellites and satellite failures are impeding progress. The development of appropriate end of life strategies for satellite de-orbit and replacement is essential in improving efficiency and reliability for service users from an operational management perspective. In order to reap all possible societal benefits of data collected in space, data sharing a distribution will play an essential role in the development of value-added Big Data products (OECD, 2016).

3.3.5 Defense:

The application of Big Data for monitoring climate change through both temporal and image data has seen unrivalled performance in space. However, using the same technologies to collect data for defense is becoming increasingly popular. Monitoring of high-risk countries for military purposes is hugely effective in the implementation of effective defense strategies. The satellites employed for carrying out this data collection are primarily completed by satellites in both the LEO and GEO domains. Traditional satellites offer a wide coverage meanwhile SmallSats and constellations can offer a better revisit rate resulting in more consistent updates and more current data which is critical for Defense in some cases.

As the needs of various military and defense organizations are evolving toward more expeditionary missions such as warfighters moving into uncharted or hostile territory, better knowledge of the environment and potential hazards can be lifesaving. SmallSats and big data have proven their potential in Defense operational systems, creating value-added propositions in military communication and image collection.

The nature of the defense industry and its operations make it a perfect candidate to benefit from the application of Big Data. Ensuring connectivity is essential in determining the best course of action with time constrained decisions. Improving operations through applications such as image recognition artificial intelligence algorithms to detect vehicle movement or outpost locations is both sensitive and potentially lifesaving. The success of such AI systems for image classification has been proven across a myriad of differing applications from mitosis detection in breast cancer histopathology images to facial recognition to sentiment classification (Chen, Dou, Wang, Qin, & Heng, 2016; Ghiassi, Skinner, & Zimbra, 2013; Jiang & Learned-Miller, 2017).

Effective management of this data to make better strategic and tactical decisions for defense sectors including military, communications, emergency services and energy is critical in terms of both maintaining diplomacy and saving lives (Johnson, et al., 2016; Watkins, et al., 2017).

3.4 Gap in Research

Having explored both the applications of big data for improved operations on Earth and the application of Big Data to the space sector, the potential benefits of adopting such techniques to maximize operational efficiency are paramount for progress. The numerous applications of Big Data for space and their effectiveness has been proven resulting in the exponential increase of activity in this sector. However, research in the area of Big Data for operations in the Space sector has been focused on improving operations on earth. Research on the potential benefits of Big Data for operations in a space to space context is extremely limited and, as such, will be the core focus for the remainder of this research paper.

Chapter 4 - Space to space

Technological improvements have been a key driver in the exponential increase in space company investment activity over the past 10 years. Improved availability of smaller and higher performing electronic components and equipment due to smaller costs are continuing to fuel increased investment in the industry (Schaller, 1997; Moore, 1965). Space to Earth technologies and informatics have seen widespread adoption by many players such as governmental agencies and information technology firms. However, the vast majority of big data applied to space is leveraged to provide value on Earth as opposed to in space. These advancements are broadening horizons for the human race. Better understanding of Earth with regard to science and politics is enabling better decision making, but only if that data is acted upon in an ethical manner (Richards & King, 2014). Space to Space analytics is a relatively new concept and will manifest as a disruptive technology.

Heightened accessibility to space is fundamental in improving life on Earth. However, this too has trade-offs. Ever decreasing satellite and launch cost is has resulted in exponential growth in the number of objects orbiting Earth (NASA, 2012). The figure below details the increase in the number of space objects in orbit by type and also overall *(Figure 3)*.

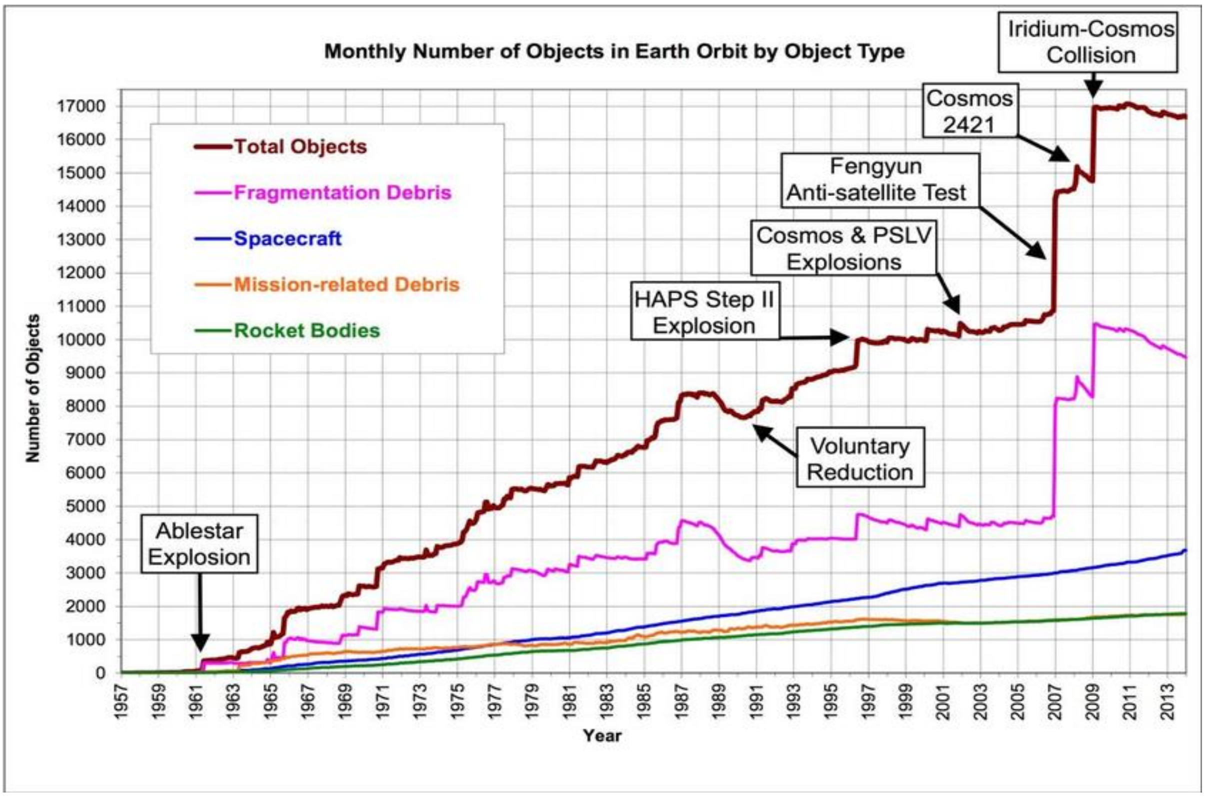

Figure 3: Number of Objects in Earth Orbit by Object Type (NASA, 2012)

The increase in the number of objects in orbit represents a significant challenge and risk for satellite providers. As such, this chapter will detail possible opportunities for Big Data as applied to satellites to improve operational management in a Space to Space context. The opportunities explored will be detailed pursuant to each pillar of improved strategy in operational management outlined in Chapter 1; Live Monitoring, Improved Reliability, Improved Efficiency and Empowering Decision Makers.

4.1 Live Monitoring

The enormous benefits of live monitoring of data in operations are improving facets of business such as operational efficiency, reliability and, is helping to ensure decision makers are empowered, knowing that they have access to all available data. Additionally, live monitoring is enabling decision makers throughout a myriad of sectors to act in a more responsive manner, enabling a more agile approach to operational management.

The dangers of increased orbiting satellite and debris were first highlighted by Kessler. His hypothesis of a cascade effect created by satellite collisions was pivotal and has since been emphasised by the amassing orbital debris caused by catastrophic satellite collisions and failure. Orbital debris is defined as the junk orbiting Earth, comprised of everything from redundant satellites to small satellite fragments. As illustrated in *Figure 2*, the increase in the number of satellites and more frequent collisions is resulting in an exponential increase in the total number of orbiting objects. This is a major safety concern for satellite launch and longevity. Big data for the live monitoring of satellite health parameters and debris presents an appropriate method of mitigating these issues.

The live monitoring of components in machinery and processes in business is now more effective than ever using Big Data analysis techniques. Furthermore, applying these same working principles to enhance operational management for space applications is paramount in maximising operational efficiency in a space to space context. The live monitoring of components to analyse satellite and satellite subsystem health could be achieved through Big Data analyses. Space is an inhospitable environment with dangers such as space debris and radiation increasing the risk of shortened satellite lifetimes (Liou & Johnson, 2006; O'Bryan, et al., 2000).

Space debris is an increasing risk for both satellite deployment and for maximising satellite lifespan. This debris, travelling at immense speeds of up to five miles per second, however small, can cause catastrophic damage to operational satellites (NASA, 2010). Implementing live monitoring techniques for collision prediction is essential in mitigating the risk of Kessler Syndrome and in the development of appropriate countermeasures such as end of life deorbiting (Kessler, Johnson, Liou, & Matney, 2010). As such, two noteworthy companies attempting to reverse the increasing risk of collisions have been founded as of late. LeoLabs, a U.S. start-up are harnessing the power of Big Data to map the LEO (LeoLabs, 2018). Whereas, Astroscale, a Singaporean company are designing satellites to carry out debris removal procedures (Astroscale, 2018).

Radiation exposure is detrimental for electronic components. Collection and analysis of radiation exposure data for predicting and pre-empting component failure in satellite systems could provide invaluable information for operations management (Benton & Benton, 2001). The prediction of such failures enables an agile and proactive approach to maximising satellite lifetimes whilst minimizing the creation of new space debris. That is, the implementation of appropriate end of life strategies to minimize potential redundant satellites becoming new space debris.

End of life strategies for failing and redundant satellites are becoming more and more necessary due to increased orbital traffic. However, in order to ensure maximum return on investment for businesses, prolonging the operating lifespan of satellites is a key focus. Conversely, minimizing the increase in space debris is important for both the viability and longevity of future space missions. As such, leveraging Big Data analysis techniques to improve operations in terms of better strategic planning of appropriate end of life strategies to essential in improving reliability, increasing efficiency and subsequently, empowering decision makers.

4.2 Enhanced Reliability

Enhanced reliability in this context will be a product of debris analysis, and proactive maintenance and replacement of redundant satellites. The benefits of enhanced reliability are numerous, including, but not limited to reduced financial risk, a core goal of operations management. The sale of satellites and services to increase reliability through predictive analytics is crucial in a Space to Space context. This is so due to the complex nature of implementing modifications on in-orbit satellites. Enhanced reliability and subsequently, increased satellite lifetime opens the possibility for potential future refuelling missions and in-orbit space reparation that can be more easily achieved with better knowledge available due to the adoption of Big data (Washington, DC: U.S. Patent No. 6,843,446, 2005). Maximising profit and reducing risk are core goals of operations management and a by-product of enhanced reliability.

Risk calculation is something inherent and determinant in the Space sector. With factors such as costly technology, low possibilities to repair in-orbit and complex launch and product development and manufacturing, avoiding any potential hazards is paramount. As such, mitigating reliability concerns can save time and money but also give confidence for costumers, investors and insurances companies.

Big data analytics are providing reliable efficient predictive models to mitigate risk and anticipate any potential future problems through understanding patterns and correlations in historical data. Through the understanding of historical patterns and correlations in data, predictive analysis is crucial in the Space to Space sector. It is also critical in constellation management where updating or replacing a satellite is a complex process which can be pre-empted to maximise reliability as the loss of one interconnected Small satellite can impact the whole efficiency and reliability of a constellation (Benedicto, Dinwiddy, Gatti, Lucas, & Lugert, 2000). In order to facilitate better operations management in a configuration like this, Big data will provide vital information to anticipate failures and ultimately, to avoid them. Also, these tools can improve satellite management through proactive maintenance to enhance the reliability of satellites for customers by providing the exact time when a future action will have to be taken and reducing possible downtime (satellite replacement, initiate new production, anticipate updates, etc.). As such, manufacturers will be able to provide more services for proactive maintenance with the satellites they create to improve management and operations, to increase revenue streams and costumer's loyalty (Reichheld, 1993).

Furthermore, increasing SmallSats reliability is a major concern for public and private sectors at both mission and component level. Indeed, if those kind of satellites were previously designed to work on missions where resiliency was a second plan concern, with higher risks compared to GEO satellite missions, the LEO market is now evolving towards longer and more valuable missions (NASA, 2018). Big data management can provide instruments to ensure risk diminution on launches and in-orbit management, a determinant aspect of operations strategy in Space market.

This risk diminution is directly linked with financial and insurance concerns. It is also vital for debris management with two different impacts. Firstly, to reduce risk of creating new debris by providing more reliable satellites. The analysis of existing debris and risk of collisions for smart satellite placement and or removal is also paramount in developing a safer space through better operations management.

4.3 Increased Efficiency

With the development of Industry 4.0, data is becoming a key tool in business to optimize strategic choices. Big Data is improving industry by analysing processes to better understand operations and subsequently providing smart insights that are allowing for the development of better management decisions in supply chain or cost reduction for example (LaValle, Lesser, Shockley, Hopkins, & Kruschwitz, 2011).

Efficiency is an important aspect of Satellite Industry, where every step of manufacturing, launching and managing the satellite can be critically impacted by a lack of performance. In a context where competitiveness is increasing, and technological improvements are progressing towards an intensification of Satellites launches, Big Data has the potential to create new value for Space manufacturers.

There is a growing need to apply the same Big Data techniques that have been proven to improve efficiency for operations on Earth to the Satellite Industry. Satellite providers could in turn benefit from important cost reduction and more scalability of their product for different applications. The implementation of such instruments can redefine the manner in which the Satellite industry operates. By optimizing the data-driven chain, providing flexibility and adaptability, they have the potential to support new technologies with impacts in terms of standardization such as Software Defined Payload, a less costly and more scalable way to conceive payloads than the traditional one by taking into account Big Data and applications (Van Duijn & Redi, 2018).

Furthermore, the challenging concept of Space efficiency is a source of new future opportunities such as refuelling missions, in-orbit reparation and reconfiguration. However, such concepts require important technological improvements and considerations to become a reality in terms of proving their potential for better efficiency in business in order to secure investment. Big Data and the instruments responsible for analysis of information gleaned also have a high capacity for adding value, finding operational inefficiencies and creating situations where competitive advantages are more easily achieved (Zhou, Fu, & Yang, 2016).

Constellations are also facing challenges in terms of efficiency for space operations. One major hurdle is Space Congestion, and, as such, availability of space is limited. This unfortunately is a constraint in the development and placement of new satellite constellations. Big Data applications are numerous for developing a better future for satellite constellations and the associated problems they face now. Finding new patterns using already existing data to highlight safer satellite placement whilst maximising constellation coverage is a very efficient way to reduce risk associated with congestion and could be applied in space to better manage satellites for example, supporting the development of a LEO-GEO constellation. With new data-driven processes, assuring more coherency with regard to constellation satellites is a way to reduce congestion and provide actionable insights to produce and deploy the most efficient configurations (Marr, 2017).

One concern of implementing these new procedures is the fact that Big Data analytics will require hardware to be installed on traditional and small satellites. The increased weight resulting from this will increase launch costs also. However, the trade-off will ultimately be beneficial with increased understanding providing the platform to maximise operational efficiency in terms of deployment, replacement and the appropriation of suitable end of life strategies (Cornara, Beech, Belló-Mora, & Martinez de Aragon, 2010).

Analytical methods can improve efficiency of operational management for Space-to-Space products and provide services to guarantee quality to customers and investors. This operational impact relates to reliability concerns, in creating new opportunities for competitiveness and profitability in the satellite industry.

4.4 Empowered Decision Makers

The benefits outlined for developing a more agile and proactive approach to making better decisions regarding space to space operations management are heavily dependent on the three aforementioned interconnected and interdependent pillars outlined. Making decisions in ambiguous circumstances is not only risky, but irresponsible. Shooting in the dark is no longer an issue. The ubiquity of Big Data is providing more information than ever. The subsequent analysis of that data is fuelling competitiveness in all industries. However, as highlighted in earlier sections these principles are applicable to improved strategic decision making in operations management for the space to space sector. Though live monitoring is detailing methods on how to enhance reliability and increase efficiency in space to space operations, these processes can be automated. The real value in harnessing the power of analytics for Big Data is in improved decision making. As such, the relationship between each of the pillars of Big Data for operations has been illustrated below *(Figure 4)*. The relationship between each and their effect on the decision-making process for improved operations management will be explained in the following excerpts.

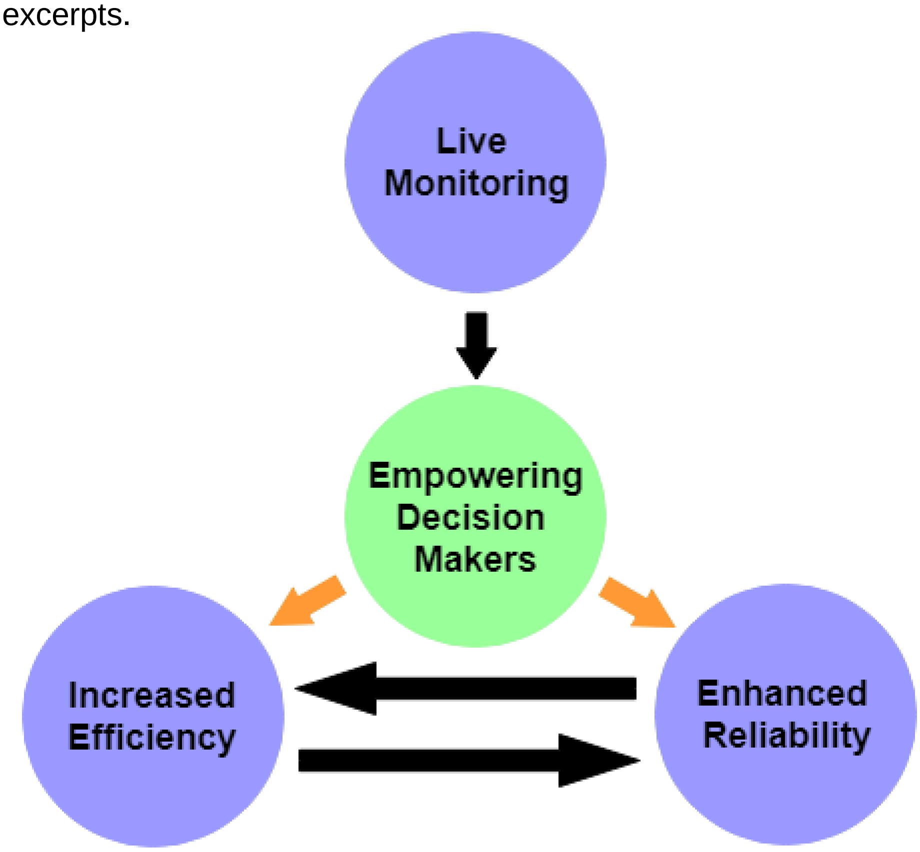

Figure 4: Big Data for Space Operations Management Roadmap

Live monitoring of components health status provides information on satellite subsystem and satellite lifetime. Leveraging this information can aid decision makers in the safe and timely removal of satellites in order to minimise the creation of new debris (Janovsky, 2002). Furthermore, descriptive analytics detailing component failure rates provide an insight into improving new satellite designs for engineering and design teams. The use of predictive analytics to determine mission lifetimes is invaluable, not in the safe deorbiting of satellites, but, also in their replacement. Doing so efficiently minimizes downtime for services requiring satellite data or operations (Tafazoli, 2009).

Reliability of services is a key performance indicator for any service provider. Constellation satellites rely on the interoperability and connectivity of a number of satellites. As such, ensuring these satellites can be replaced if failure occurs is imperative to offer the best service possible to customers. This has been traditionally achieved by installing redundant backup subsystems. However, this increases satellite mass and, subsequently, cost (Richharia, 2017). Enhancing the reliability of systems is mutually beneficially for improved operational efficiency also. Operations management can ensure that satellites at risk of failing are replaced in a timely manner. Much of the demand that constellation satellites attract is dependent on coverage (Lang & Adams, 1998). As such, the loss of a satellite from a constellation can be extremely costly. Initiating appropriate operational management strategies to minimise this risk is beneficial in terms of reduced redundancy and increased robustness of a constellation network (Benedicto, Dinwiddy, Gatti, Lucas, & Lugert, 2000). However, these principles also apply to satellite and SmallSat operations.

Improving efficiency in the operational management of satellites is also closely linked to reliability of services. However, it is the efficient replacement of redundant or failing satellites that ultimately determines the reliability of service (Washington, DC: U.S. Patent No. 6,843,446, 2005). That includes the timely manufacture of satellites in need of replacement in order to minimise downtime. Furthermore, leveraging Big Data in planning of satellite placement to reduce risk from life shortening factors is also a major consideration. The efficient implementation of appropriate end of life deorbiting strategies and seamless replacement is a Key Performance Indicator (KPI) in the continuous improvement of space to space operations. That is the analysis of big data acquired in space to optimise operations in order to maximise the efficiency of operations in the space industry.

The interconnected relationships of each of the pillars detailed is complicated. However, each is necessary to ensure the best possible outcomes for improvements in operations management. The Big Data centric approach improved operations management in a space to space context is paramount in a myriad of performance facets, most notably; improved satellite lifetimes, increased network robustness, better services and finally in minimising the creation of new space debris.

Chapter 5 - Conclusion

The influx of Big Data across all industries over the past 10 years has been driven by both proof of concept and an increased awareness of the benefits of analysis of such data (Chen, Mao, & Liu, 2014). The increase in information available and the subsequent analysis of this data is improving the manner in which businesses conduct their affairs. Similarly, the space industry has been subject to exponential growth in the past 20 years. Technological improvements are a motivating force in both the increased availability of satellites for differing applications and the reduction in costs associated with each.

The CRISP DM framework of mapping business understanding to actionable insights is an industry standard. Applying such a framework to alleviate bottlenecks in operations by leveraging data is essential in the development of appropriate strategies to improve operations management in the satellite industry. However, Big Data for the analysis of system diagnostics overall satellite health is a relatively new concept, and, as such, requires further work.

The benefits of Big Data for operations have been detailed under four main headings; live data, enhance reliability, increased efficiency and empowering decision makers. Though this topic has been well researched for terrestrial applications, research in a space to space context is lacking.

The space industry and applications of Big Data in space are well documented. However, this area was investigated in order to develop a fuller understanding of industry applications and processes in the development of our argument.

This paper focuses on building a full picture of Big Data, the development of strategies and processes used to capitalise on Big Data and the potential of such services for improved operations management in a space to space context. Despite the mass adoption of Big Data on a global scale, little research in the context of space to space applications has been carried out. Furthermore, operations management is a core process of any business but academic and scientific research in a space to space context is limited. This paper works to bridge the gap between Big Data and Operations Management in a space to space context. However, more research on the benefits hypothesised is needed to develop a comprehensive and feasible method for deploying such technologies in order to maximise operational efficiency.

The primary objective of this paper was to explore and assess the potential benefits of leveraging Big Data to improve operations management in a space to space context. As this is an area of much ambiguity, all research has been heavily referenced to ensure a compelling argument. Space debris presents a significant and growing problem for satellites. As such, our research provides an in-depth insight into better operations management for satellite companies in order to minimise the creation of new debris with analytics providing decision makers with all the tools necessary to instigate the safe removal of failing satellites. The adoption of such policies will pave the way for a safer future satellite habitat, however, may need to be legislated upon to enforce such a change. Furthermore, adopting Big Data for satellites in a space to space context will enable satellite companies to offer the best possible services by increasing satellite lifetimes, minimising downtime and maximising performance of those satellites. Finally, adopting a smart approach to operations management in a space to space context by leveraging Big Data will pave the way to maximising profits.

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