Multi-Criteria Optimization for Cybersecurity Risk Management in Space Mission Supply Chains

Bartosz Sawik

Space Technology Department
AGH University of Krakow, Poland
barsaw@agh.edu.pl

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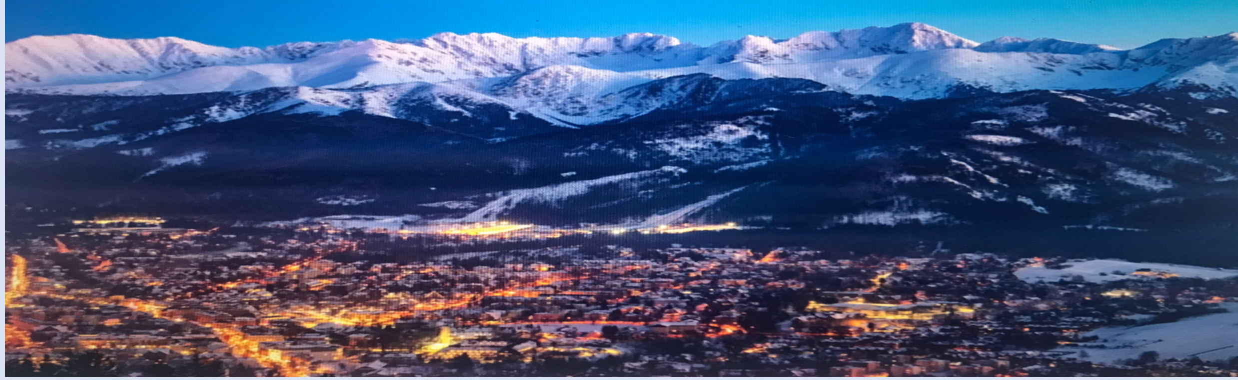
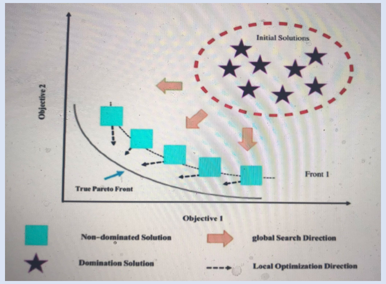


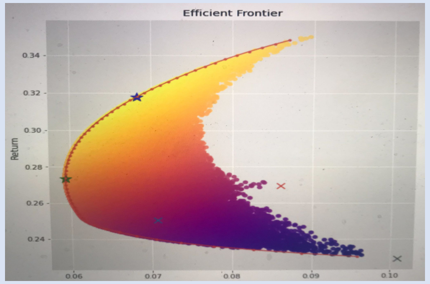
POLAND:

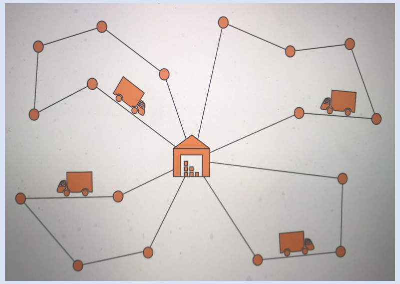
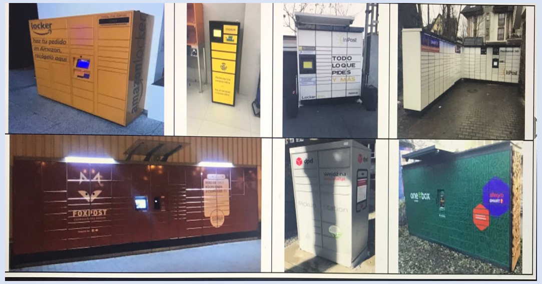
- Erasmus+ Agreement Coordinator (Spain(E), Austria(A), Portugal(P), Iceland, BG, IZ).
- Innovation Projects Evaluator NCR&D(+38) i BrigdeAlfa NCBiR (3), PARP(+9), Mazovia Innovators (9; +3).
- Supporting Supervisor of finished Ph.D. Thesis at AGH (2; +2).
- Supervisor MGR(Master), INŻ.(Ing.Bachelor) – ERASMUS Final Projects (+25 E,P, +2), AGH (+8)
- Research Grant (1 MNiSW (Ph.D. Thesis “Promotorski”), 2 National Research Center - NCN)

ABROAD:

- Visiting Professor (22 months & 3 months UPNA Pamplona; 1 month UPV Alcoi)
- Visiting Scholar (E, A, P, UK, USA; +15), Erasmus Teaching (E, A, P; +10)
- Ph.D. Thesis Reviewer (3 E).
- Research Grants (5 E; + 2 E ongoing; 8 PL; + 2 PL ongoing)






2025: Habilitation process ***"*****Multi-criteria optimization methods for decision support in various service systems** *(Metody optymalizacji wielokryterialnej do wspomagania decyzji w różnorodnych systemach obsługi)"* **-** Informatyka Techniczna i Telekomunikacja (**Operations Engineering/Computer Science**).

2020: Master of Didactics in Excellent Teaching, ST Learning Lab, Faculty of Science and Technology, Aarhus University, Aarhus, Denmark

2019: Executive Course on University Management, University of Helsinki, Helsinki, Finland

2013: TOP500Innovators**. Executive Course on Innovation and New Technology in Science,** HAAS School of Business, University of California at Berkeley, USA.

2012: Ph.D. in Operations Research/Automatics and Robotics (with special honors), Dissertation in English: "*Multi-Objective Portfolio Optimization by Mixed Integer Programming*". Faculty of Electrical Engineering, Automatics, Computer Science and Electronics, AGH University of Science & Technology, Kraków, Poland

Research

- Multi Objective Portfolio Optimization (Value-at-Risk, Conditional Value-at-Risk)
- Multi Criteria Vehicle Routing Optimization Models
  - for Green Logistics of Goods for Grocery Store Chain
  - for Supply Chain with Risk consideration (VaR, CVaR)
- Optimization of Assignment of Robots for Elderly Care
- Multi Criteria Optimization and Assignment of Services in Hospital
- Optimization of Automated Parcel Lockers Location
- Multi-Criteria Optimization of Prices on Electricity Market
- Multi-Criteria CyberSecurity Portfolio Optimization
- Multi-Criteria Supply Chain Portfolio Optimization with Risk

Methods

- Multi-Criteria Optimization (Fair, Weighted, Lexicographic, Reference Point)
- Mathematical Programming
- Exact Approach vs. Approximation Algorithms
- Mixed Integer Programming with Linear Constraints
- Optimization: CPLEX, GUROBI, AMPL

Space Technology

- Supply Chain for Space Mission
- Optimization Models including Risks (VaR, CVaR) for Space Mission
- CyberSecurity in Space Mission Planning
- Digital Twin and Metaverse with Multi Criteria Optimization of Planned Space Mission: Conditions, Modelling, Mitigation of Risk

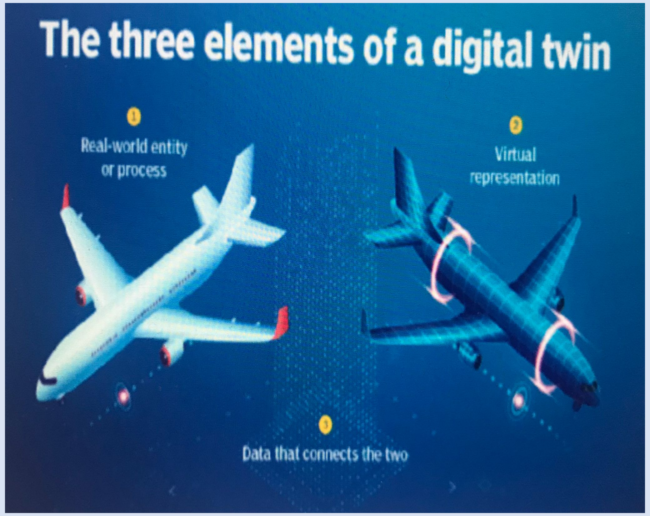
Multi-Objective Optimization Model for Space Mission Planning

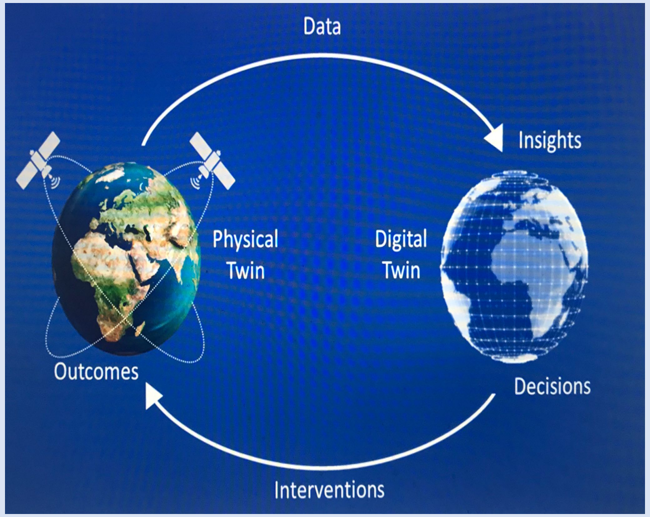
- Example of Criteria
  - Minimization of stress levels related with space mission preparation.
  - Minimization of risk factors related with space missions.
  - Minimization of costs of space missions.
  - Minimization of time required for space mission preparation.
  - Minimization of time required for space mission tasks.
  - Maximization of efficiency of resource allocations.
  - Maximization of resource utilization.
  - Maximization of sustainability of space missions.
  - Maximization of the safety level of space mission accomplishment.
  - Maximization of supply chain efficiency.
  - Maximization of a set of resilient suppliers.
  - Minimization of disruptions in the supply chain.
  - Minimization of space mission components vs. Maximization of space mission tasks.

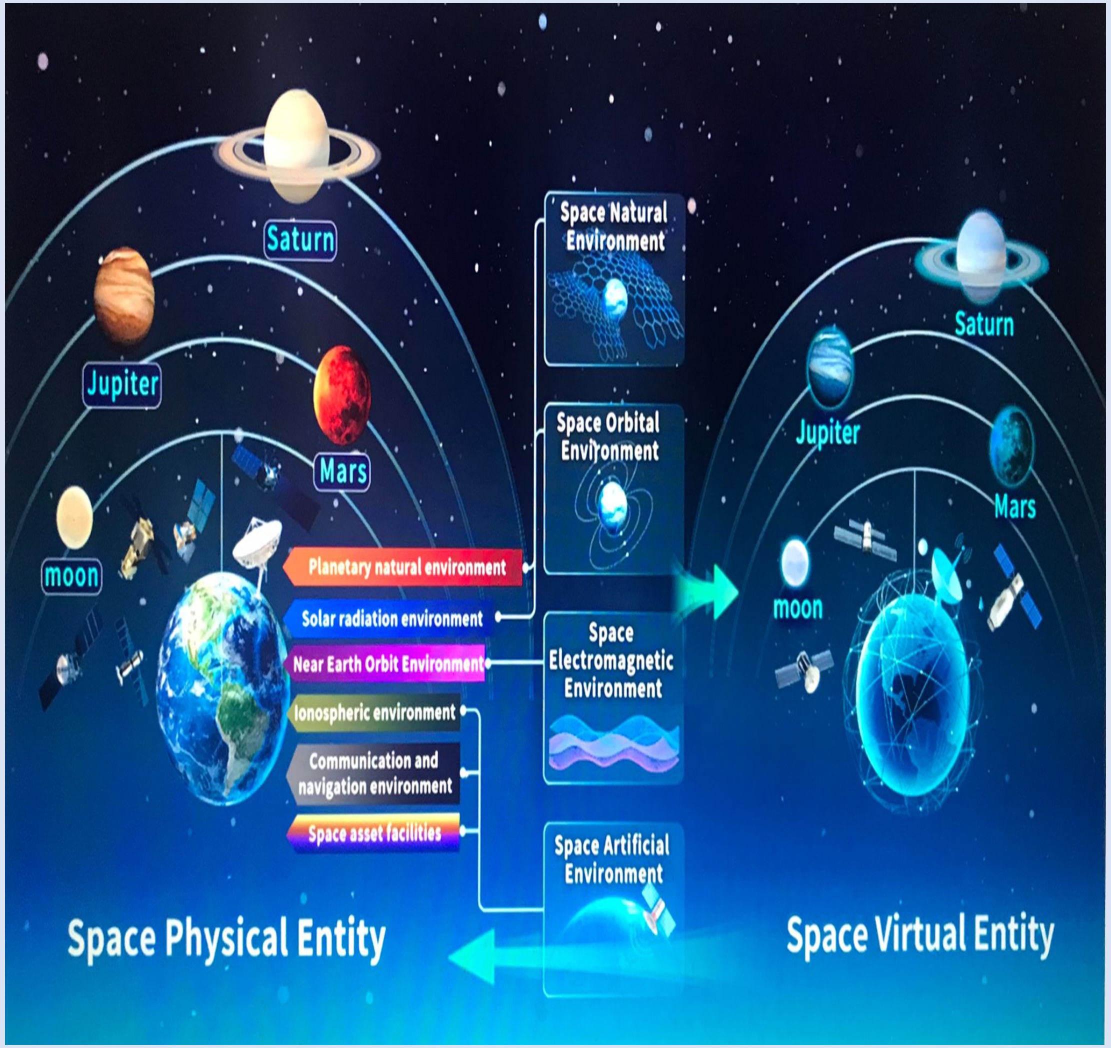
Single- vs. Multi-Criteria Space Mission Planning

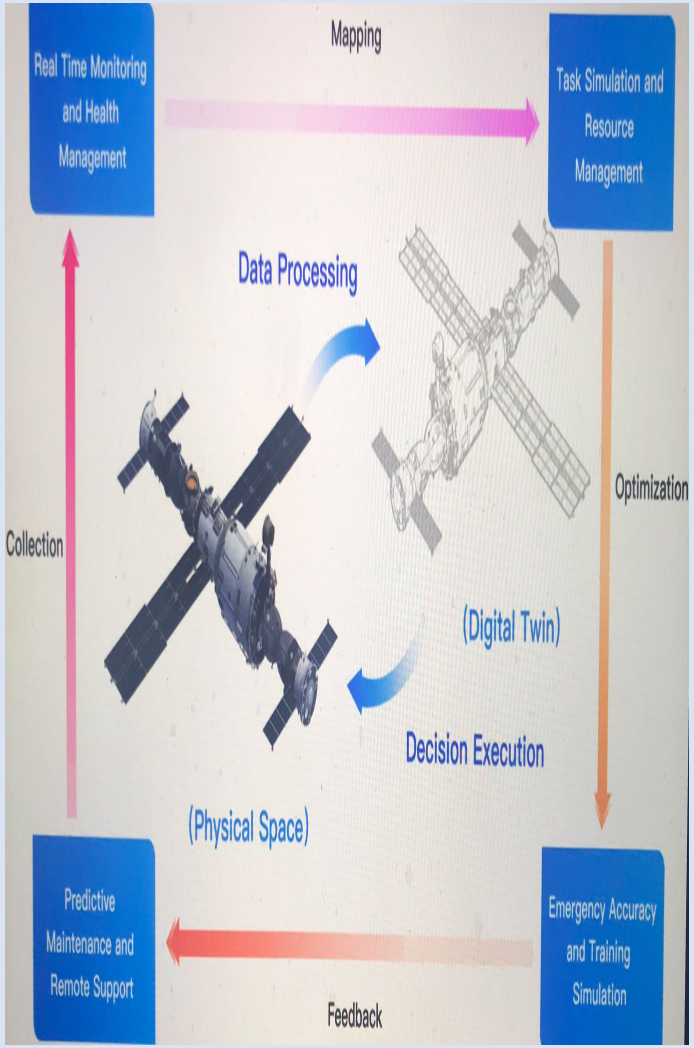
Stage 1: Input data for the optimization model				
Stage 2: Building optimization model for space mission	A single objective optimization approach	Multi-Objective optimization approach		
Stage 3: Criteria definition	Risk	Minimization of space mission risk(s)	Maximization of space mission sustainability	Maximization of space mission supply chain efficiency
	Sustainability			
	Supply Chain			
Stage 4. Analysis of results	Three independently computed single objective models.	One multi-objective computed model with a non-dominated set of pareto solutions connected to each other. Each criterion has an impact to another criterion.		
Stage 5. Decision-maker choice based on obtained results.	No relation between the criteria. Choice is limited, due to the not calculated impact between risk, sustainability, and supply chain structure.	Decision maker is capable to choose the best decision alternative from the inter-connected solution from a non-dominated set of pareto solutions, showing the relations between risk, sustainability, and supply chain efficiency (structure/portfolio of the optimal set of suppliers). All relations are included in the model and reflected in the results.		
Stage 6. Evaluation of chosen solution by the decision maker	In terms of: costs, time, efficiency, quality, security, reliability, resiliency, and robustness. In terms of: sensitivity control of the formulated mathematical model and results.			
Stage 7. Implementation	The optimal set of tasks, components, and suppliers required for a successful space mission.			
Stage 8. Reevaluation during space mission preparation due to randomness factors, which could appear in time.	The decision maker includes randomness factors and repeat steps from Stage 1. To Stage 7. if needed.			

Digital Twins









Digital Twins vs. Multi-Criteria Optimization

- Challenges:

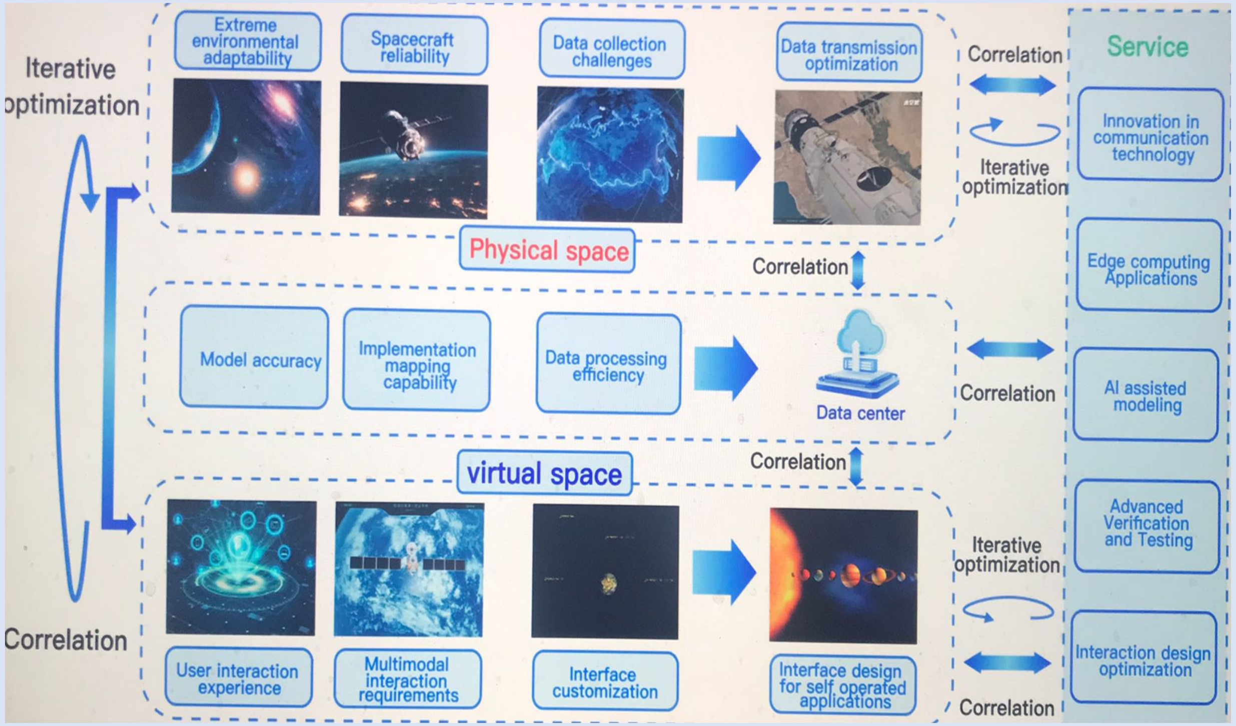
- Data transmission delays, model accuracy, design of user–system interactions

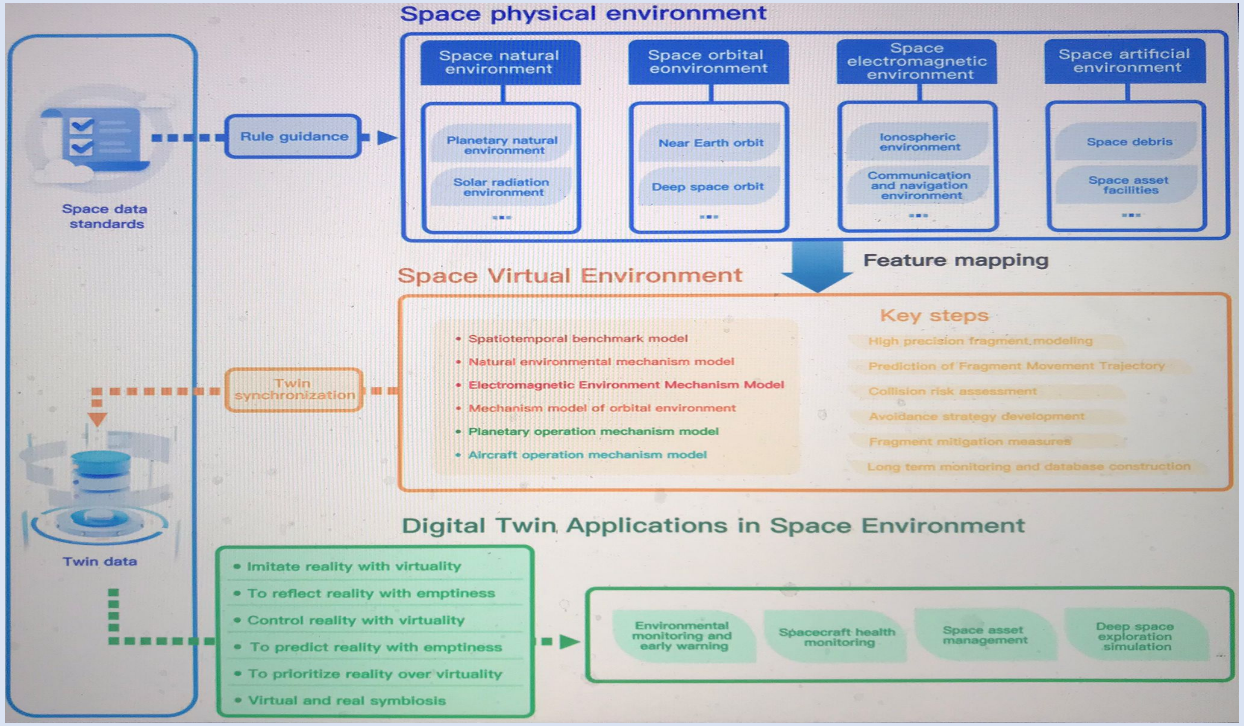
- Fault detection and diagnosis algorithm (pattern recognition, machine learning, other methods to identify abnormal behavior, timely detection of potential faults)

- Optimization and control algorithms: physical models and real-time data

- Optimization the performance of physical entities: fuel consumption, orbit adjustment, cost, time, risk, efficiency, etc.

- Digital Twins as a Tool for Space Environment by Using Virtual Modeling





- Advantages:
- Enhance the safety and reliability of space missions by creating precise virtual models
- Provides a powerful tool to enhance the safety of: spacecraft, space stations, space mission
- What if analysis and scenarios
- Not only helps to improve spacecraft (tool) design and maintenance processes, but also enhance the efficiency of mission planning and execution

Metaverse (Virtual Reality)

Metaverse Applications for Space

The Metaverse is a new wave of disruption shaping the Space Industry's future. The below applications are meant to be thought provoking, and not exhaustive:

Integrated Simulation Training

Hyper-realistic training within the Metaverse could provide unique capabilities. Training in VR could overcome associated costs, pre-screen candidates, mitigate risks, and replicate scenarios that were otherwise impossible.

Potential scenarios:

- Scaled Launch & Mission Control Simulations
- Component Level Authentic Astronaut Training
- Architecture & Layout Planning

Connected Worker

Extended Reality (XR) can dynamically connect workers to information enabling them to be more efficient, accurate and safer. From human-robot collaboration to digital twin overlays such as schematics or live sensor feeds.

Potential scenarios:

- Digital Twin Operations
- VR Human-Robot Collaboration
- Space R&D Inspiration
- Astronaut Remote Assistance

Consumer Experiences

The Metaverse presents a new channel to engage consumers with a diverse set of experiences, to form new kinds of communities. Ultimately, this can help players engage a new audience via an internet of place and ownership.

Potential scenarios:

- Interactive Space Museum
- Immersive Space Walk
- Form powerful communities via tokenised access

Geospatial Metaverse

A fusion of geospatial data and Metaverse capabilities can unlock entirely new possibilities. From precise location services to hyperspectral satellite imagery to photogrammetry to LiDAR scanning.

Potential scenarios:

- Lunar Surface Modelling
- Earth Oberservation Visualisation
- Smart City Planning
- Remote Areas Intelligence

Value of VR for Space R&D

A virtual reality collaborative experience to inspire innovation and simulate the experience of conducting Space R&D experiments in virtual locations:

Inspire AND **Simulate**

Inspire

Ideation Inspiration

Inspire ideation for **potential experiments and mission life cycle improvements** through workshops in the virtual space

Mission Optimization

Identify **data-driven insights** to unlock opportunities for optimization of future space missions

Business Pipeline

Create **future business pipeline** for space missions by inspiring clients to uncover the benefits of R&D in space via a simulated mission on earth

Backlog Development

Enable the co-development of a comprehensive **backlog of scientific experimental concepts** to investigate in future simulations

Simulate

Experimentation

Replicate space experimentation processes, such **as cell division or a bespoke experiment,** in virtual reality environment

High-Risk Steps

Mock steps in the virtual environment for planning purposes: defining requirements, **de-risking the mission, and estimating timeline to launch**

Communication

Practice clear communication with **mission control specialists, astronauts, and researchers** to ensure smooth integration a

Payload Processing

Simulate following a payload in space or ISS, understanding the **mission parameters with data visualizations**

Expanding traditional boundaries of the Space economy for existing participants and lowering barriers for new entrants.

Space technology has become more accessible, economical, and better positioned for global businesses. Participating in Space means more than exploration, it includes using **Satellite images and AI** for detection and predictions, **mission control** for **experiments** and payloads, providing **products and services** within the Space ecosystem, and developing the new **infrastructure**.

Change Triggers & Trends:

- Lower launch costs and flexible payloads offer affordable access;
- The democratization of Earth observation data from satellite providers;
- Collaboration between private and public entities;
- Expanding opportunities beyond the traditionally held boundaries

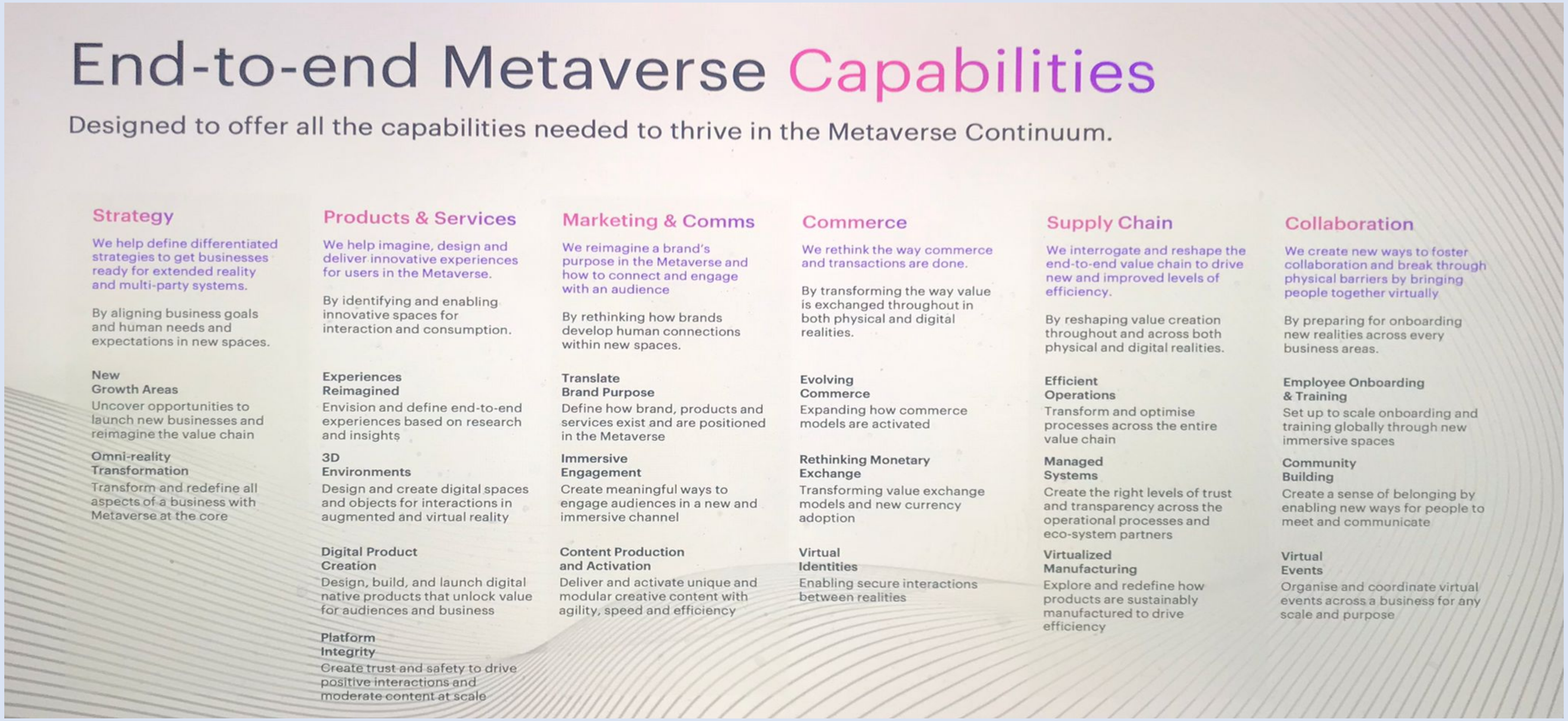
Metaverse for Space Mission Planning

- Challenges:

- Data Integration and Accuracy
- Hardware and Software Limitations

- Advantages:

- Immersive Visualization and Simulation
- Cost-Effective Prototyping and Testing



- Application of Metaverse for supporting:
- Earth to Space - Space-as-a-Service: Mission Control, human space flight
- Space to Earth - Repurposing Space tech for use on Earth
- Space and Beyond - Space Supply Chain (Lunar, Mars missions)

Multi-criteria optimization approach combines all the aspects of Space Mission in a complex model

Example of (Case Study) Applications (MCO+DT+MV)

- Lunar dust adhesion vs. "car windshield wipers" - solution (automatic cleaning brush with dust sensors vs. resilient material) - digital twin mitigation model in metaverse with MCOM
- Moon mining (extraction) of Helium 3 - MCOM, metaverse, digital twin
- Space base/village planning - MCOM, metaverse, digital twin
- Mission planning - MCOM, metaverse, digital twin
- Disaster scenario planning - MCOM, metaverse, digital twin
- Cooperative game with fair multi-criteria optimization for space mission international supply chain (Conditional Service Level at Risk, Conditional Value-at-Risk) - MCOM, metaverse, digital twin

Case Study of Space Mission Preparation: Risk Management, Optimization, and Cybersecurity (constellation of satellites vs. human mission)

- Overview of Space Mission Preparation: Traditional vs. Digital Twin Approaches
- Supply Chain Risks and Resilience: Conventional vs. Digital Tools
- Multi-Criteria Optimization: Traditional vs. Digital Twin Optimization
- Cybersecurity Risks: CVaR & VaR in the Real vs. Virtual Environment
- Integration of Cybersecurity and Financial Risk Management
- Post-Launch Risk Management: Digital Monitoring vs. Traditional Tracking
- The Future of Space Mission Planning in the Metaverse
- Integrating CVaR and VaR in Multi-Criteria Decision Making for Space Mission Planning and Conducting

Overview of Space Mission Preparation

- **Traditional Approach:**
  - Space mission planning is typically managed by teams with years of experience and relies on physical prototypes, paper-based models, and manual simulations and optimizations
  - In theory the process is mixed integer, with limited interactivity or real-time adjustments
- **Digital Twin Approach:**
  - **Digital twins** are virtual replicas of the physical assets (e.g., spacecraft, launch vehicles) and mission infrastructure
  - Provides **real-time monitoring** and the ability to run **simulations and optimizations** in a virtual environment before actual deployment
  - Enables a **feedback loop** where the mission can be tweaked digitally before actual execution
- **Metaverse in Space Missions:**
  - The **metaverse** can serve as an immersive, collaborative environment for mission planning, enabling stakeholders to interact with digital models of the spacecraft, mission assets, and mission control centers
  - Allows for more **interactive design** and virtual testing, enhancing decision-making

Supply Chain Risks in Space Mission Preparation

- **Traditional Approach:**
  - Risk management is based on physical models of supply chains, such as flow charts, risk assessments, and logistics plans, using spreadsheets and traditional tools (simulation, optimization models)
  - Disruptions are detected after they occur, requiring **manual adjustments**
- **Digital Twin Approach:**
  - **Digital twins** of the supply chain allow for **real-time tracking** of component shipments, assembly status, and potential risks
  - Allows simulation of supply chain disruptions, helping to plan for **unexpected delays** or failures before they happen
  - Improves **proactive decision-making** by visualizing how disruptions impact the overall mission timeline
- **Metaverse:**
  - The **metaverse** provides a virtual platform to collaborate with suppliers and contractors in real-time, simulating potential scenarios and testing contingency plans in a shared virtual space
  - Enhances cross-team communication, enabling faster and more informed decision-making in case of supply chain issues

Importance of Supply Chain Resilience

- **Traditional Approach:**
  - Resilience is built through traditional **risk assessments**, diversification of suppliers, and physical stockpiles
  - **Manual updates** based on historical data, market trends, and forecast reports
- **Digital Twin Approach:**
  - **Dynamic resilience** through constant monitoring of the supply chain’s digital twin. Simulations help identify potential weak spots and mitigate risks in real-time
  - Real-time updates from digital twins help organizations **adapt quickly** to changes in component availability or transportation
- **Metaverse:**
  - The **metaverse** allows space mission teams to test and collaborate on contingency plans in a **virtual environment**, ensuring the team is prepared for various risk scenarios without the cost or time delay of real-world testing

Multi-Criteria Optimization

- **Traditional Approach:**
  - Optimization is performed using **mixed integer programming (exact and approximation approach)**, **Gantt charts**, and **spreadsheets**, manually balancing Time, Cost, Quality, and Risk
  - Decision-makers often face delays in receiving updated information about mission progress and resource availability
- **Digital Twin Approach:**
  - Digital twins allow for **real-time optimization** of mission parameters based on live data, adjusting for constraints like cost, schedule, and available resources
  - **Advanced algorithms** can simulate multiple potential outcomes, guiding the optimization of time, cost, and quality based on dynamic, real-time variables
- **Metaverse:**
  - The **metaverse** provides a collaborative virtual space where stakeholders can **interactively** modify mission parameters (cost, schedule, resources) and immediately see the impact in the virtual environment
  - **Simulations** in the metaverse allow for a more **holistic decision-making process**, considering the perspectives of all involved parties

Time Optimization in Space Missions

- **Traditional Approach:**
  - Time optimization is typically done using **manual scheduling** tools like PERT and CPM
  - **Delays** may not be discovered until later in the process, resulting in cascading effects on the mission timeline
- **Digital Twin Approach:**
  - Digital twins can simulate time constraints in the mission planning phase, identifying the **most time-efficient schedule** by simulating real-time data and potential disruptions
  - **Predictive analytics** allow the system to suggest **alternative timelines** based on different risk scenarios
- **Metaverse:**
  - In the **metaverse**, all stakeholders can virtually walk through the mission schedule, identify potential delays or bottlenecks, and collaboratively optimize timing before real-world implementation

Cost Optimization

- **Traditional Approach:**
  - Budget management relies on historical data and spreadsheets to balance costs, often with limited visibility into unexpected cost overruns
  - **Manual risk assessments** for cost are updated periodically
- **Digital Twin Approach:**
  - **Real-time cost analysis** and optimization via a digital twin of the mission budget and supply chain allow for continuous updates on expenses
  - Digital models provide insights into potential **cost savings** by predicting outcomes of different resource allocations
- **Metaverse:**
  - The **metaverse** can simulate the financial impact of various decisions, allowing teams to collaboratively assess **cost implications** before committing to any actions in the real world

Quality Assurance in Space Systems

- **Traditional Approach:**
  - Quality is assessed through **manual inspections**, physical testing, and scheduled validation
  - **Human intervention** is often required to detect issues, which can cause delays
- **Digital Twin Approach:**
  - **Virtual quality testing** through digital twins allows for **non-intrusive testing** of spacecraft and components in a simulated environment, reducing the need for physical prototypes
  - **Automated diagnostics** within the digital twin detect potential quality issues early in the process
- **Metaverse:**
  - Quality assurance is taken further by using the **metaverse** for **immersive testing**—allowing virtual walkthroughs and simulations of the spacecraft under various conditions to ensure all systems meet mission standards

Cybersecurity Risks in Space Missions

- **Traditional Approach:**
  - Cybersecurity is handled through **physical protocols**, firewalls, and encryption methods
  - Cyber risks are assessed through periodic vulnerability assessments and intrusion detection
- **Digital Twin Approach:**
  - The **digital twin** can simulate cyberattacks, assessing the vulnerabilities of satellite systems in a **virtual space** before actual deployment
  - **Predictive modeling** can help forecast potential cyber threats based on historical data and external inputs
- **Metaverse:**
  - In the **metaverse**, the entire mission infrastructure can be modeled and attacked in a controlled virtual environment, allowing teams to understand and mitigate cybersecurity risks without impacting real systems

Conditional Value-at-Risk (CVaR) in Cyber Risk of Space Mission

- **Traditional Approach:**
  - CVaR is manually calculated using historical data and assumptions to estimate the impact of extreme cyberattacks
- **Digital Twin Approach:**
  - CVaR can be continuously calculated and updated in real-time through digital twin simulations, offering more accurate predictions of **cyber risk** in dynamic mission environments
  - Allows for the testing of various risk scenarios and the modeling of worst-case cyberattack consequences
- **Metaverse:**
  - Cybersecurity simulations in the **metaverse** provide a more interactive platform for exploring high-risk cyber events, enhancing the understanding of **CVaR** in a virtual environment

Value at Risk (VaR) in Financial Risk Management of Space Mission Planning

- **Traditional Approach:**
  - VaR is estimated using historical financial data and risk assessment models to predict potential losses
- **Digital Twin Approach:**
  - A **real-time financial model** within a digital twin environment allows for continuous updates to VaR, factoring in current market conditions, mission delays, and unforeseen expenses
- **Metaverse:**
  - Using the **metaverse**, teams can collaboratively adjust financial risk parameters in real-time, observing the financial impact of different mission decisions before committing real funds

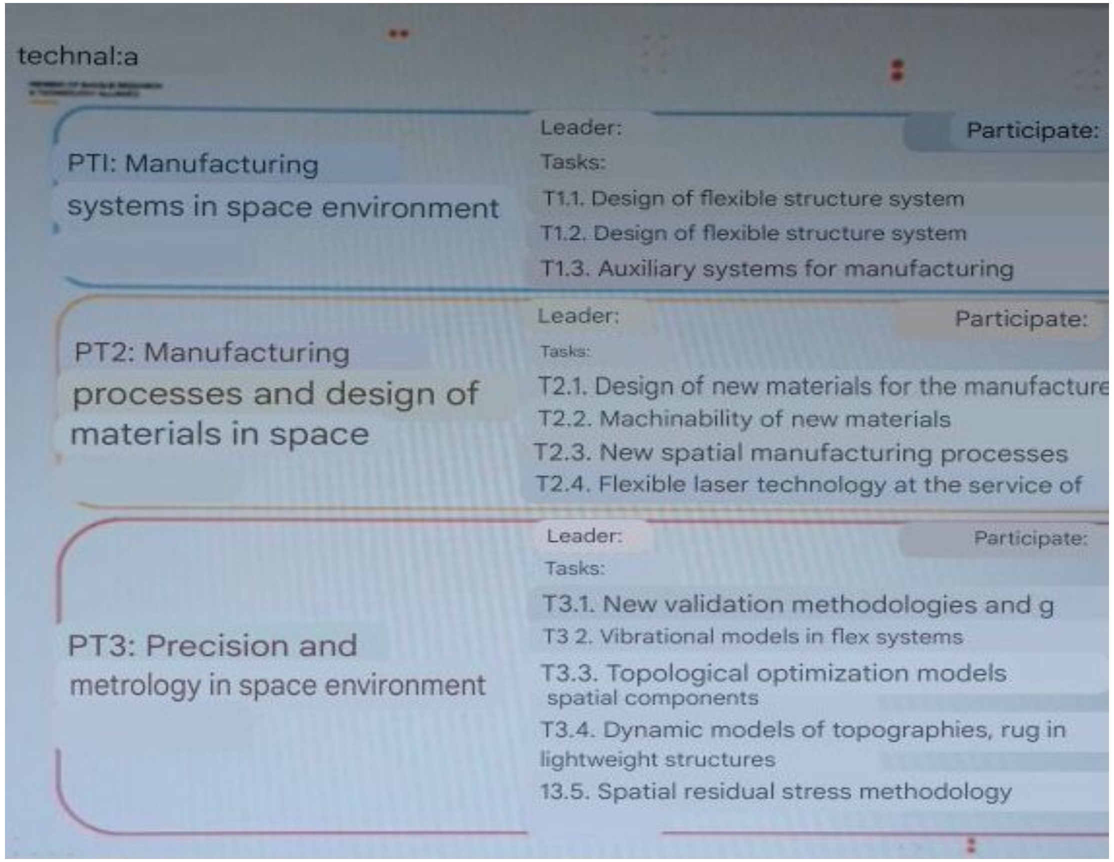
Integrating CVaR and VaR in Multi-Criteria Decision Making for Space Mission Planning and Conducting

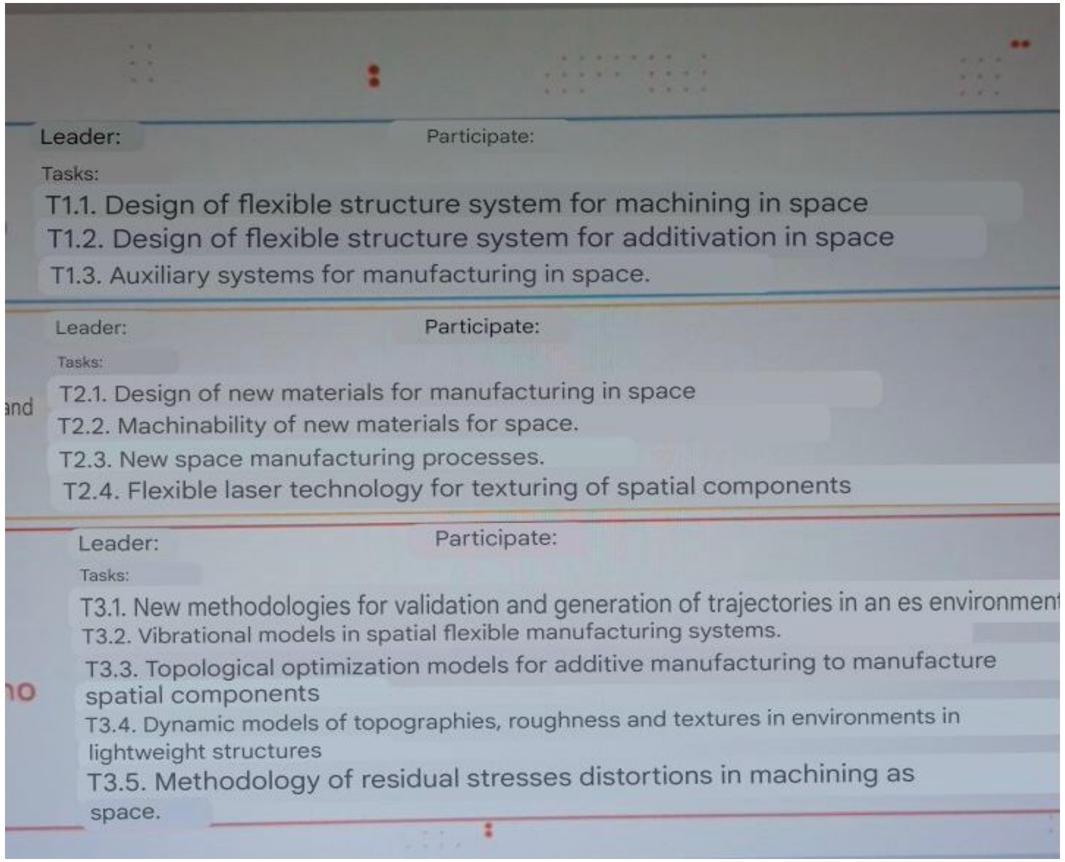
- ***Traditional Approach:***
  - CVaR and VaR are used separately to assess cyber and financial risks, with adjustments made in isolation based on predictions and historical data
  - These methods often rely on **static risk assessments** and **predefined scenarios**, which limit flexibility and adaptability in the face of real-time mission dynamics
- ***Digital Twin Approach:***
  - By integrating **CVaR** and **VaR** into the **digital twin**, real-time adjustments are made as the mission progresses, offering more adaptive and dynamic risk management
  - This integration enables **holistic risk assessments**, where **cybersecurity** and **financial** risks are assessed together in a unified, real-time environment
  - Allows for **continuous monitoring** of both financial and cyber risks, adjusting risk management strategies dynamically based on real-time mission data
  - **Predictive analytics** within the digital twin model help forecast potential high-risk scenarios, optimizing the decision-making process
- **Impact of Real-Time Integration**:
  - Decision-makers can evaluate the **trade-offs** between cost, schedule, quality, and risk **simultaneously** using a comprehensive risk framework
  - Offers a more **robust decision-making process** that takes into account **interdependencies** between different types of risk (e.g., financial and cybersecurity)

Multi-Criteria Optimization for Supporting Manufacturing Processes in Design of Materials in Space Environment

Research Collaboration

Bartosz Sawik & Alain Gil Del Val (Technalia, Spain)





Conclusions

- **The main limitations of multi-criteria optimization for space mission planning/space technology:**
  - data availability, complexity and uncertainty, trade-offs and conflicting objectives, dynamic nature of space exploration

- **The applications of multi-criteria optimization models with use of digital twin and metaverse has of paramount importance:**
  - a comprehensive understanding of the all important factors involved in space exploration, different risk scenarios, “What if” analysis, etc.

- **Importance of Space Technology Research in the context of dual-, triple-, or multiple-use of technologies:**

  - **Dual- and multiple-use technologies drive innovation across sectors:** Space research leads to the development of advanced technologies (e.g., satellite communication, GPS, remote sensing, AI for autonomy) that have both civilian and military applications
  - For example, Earth observation satellites help in climate monitoring (civilian use) and surveillance (defense use), making investments in space research highly efficient and impactful across domains

  - **Strategic and economic competitiveness:** Nations that invest in space research gain strategic advantages through multi-use assets—like satellites for navigation, communication, and intelligence—while also boosting their economies through commercial spin-offs (e.g., satellite internet, precision agriculture)
  - This strengthens national security, scientific leadership, and global competitiveness simultaneously

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