SySTEAM mini-conference

July 27th & 28th, 2023

Virtual/online

Pre-reading packet

Content

Day 2

Session 3

[Poster] **Proposal of a method to foster systems thinking using visual thinking strategies**
Akihiro Kitahara, Makoto Ioki

[Paper] **Integrating system safety engineering into STEM education**
Christopher Green

[Paper] **For the journey to expertise in systems engineering, enhance the path with Shu Ha Ri**
Fred Robinson

[Paper] **Human systems integration: from STEM to STEAM**
Guy André Boy

Session 4

[Paper] **Systems thinking in emergent behavior analysis summer internships**
Kristin Giammarco, Michael Collins, John James, and Michael (Misha) Novitzky

[Poster] **Azusa Pacific University CubeSat program**
James D. Johansen

[Poster] **Safety third: a case study for a project-based approach to systems engineering education**
Chris Brown

Note

The content on the following pages are papers and posters contributed by authors selected to present at the 2023 mini-conference, which are being shared with mini-conference attendees with permission of the authors. Copyright to the content of the papers and posters included on the following pages belong to the author(s) except where indicated otherwise by citations. If you wish to reproduce or re-use any of the content on the following pages, please make sure to obtain the permission of the associated author(s) first.

Systems Engineering Education Shortfalls With Respect To INCOSE 2035

Robin R. Rose
Belcan

Abstract. In 2022, INCOSE published "Systems Engineering Vision 2035" which was "intended to inspire and guide the strategic direction of systems engineering for the global systems community." [1] This vision was created and documented by a group of leaders from the systems engineering community, including those from industry, academia, and the government. As such, it should be considered as a valuable guide in surveying the available formal systems engineering education in the U.S. to ascertain whether the education currently available meets the needs and future needs of the systems engineering community. In this paper, the goals, challenges, and needs of the systems engineering community are compared to the formal education offered by the top 10 U.S. schools offering systems engineering bachelor's degrees. The list of the top 10 undergraduate programs in the U.S. was obtained from College Factual on the internet (website https://www.collegefactual.com/majors/engineering/systems-engineering/rankings/top-ranked/#google_vignette). The schools selected as the top 10 were selected based on several factors, including early career earnings, student debt, number of degree completions, accreditation, demand, and resources provided to the students, among other criteria. A review of the curriculum posted by these 10 Universities on the internet was performed in order to compare and contrast the systems engineering undergraduate programs of the top 10 schools and to identify gaps. The results of the survey and the gaps identified are presented. Finally, the set of innovative approaches to systems engineering skills development and enhancement that Belcan has put in place to ensure we field top-notch systems engineers who are ready for current and future customer needs is discussed.

Keywords. Future of systems engineering, INCOSE 2035, vision, trends, needs, gap assessment, undergraduate systems engineering programs, skills, proficiencies**,** curricula

Introduction

In 2022, INCOSE published "Systems Engineering Vision 2035" which was "intended to inspire and guide the strategic direction of systems engineering for the global systems community." [1] This vision was created and documented by a group of leaders from the systems engineering community, including those from industry, academia, and the government. As such, it should be considered as a valuable guide in surveying the available formal systems engineering education in the U.S. to ascertain whether the education currently available meets the needs and future needs of the systems engineering community.

The vision identifies that there are systems engineering goals or "challenges" that fall within five categories; Applications, Practices, Tools & Environment, Research, and Competencies, and stipulates that accomplishment of these goals is needed to achieve the future state of systems engineering. Per the INCOSE 2035 Vision:

- "Systems engineering contributes innovative solutions to major societal challenges.
- Systems engineering demonstrates value for projects and enterprises of all scales and applies across an increasing number of domains.
- Systems engineering anticipates and effectively responds to an increasingly dynamic and uncertain environment.
- Model-based systems engineering, integrated with simulation, multi-disciplinary analysis, and immersive visualization environments is standard practice.
- Systems engineering provides the analytic framework to define, realize, and sustain increasingly complex systems.
- Systems engineering has widely adopted reuse practices such as product-line engineering, patterns, and composable design practices.
- Systems engineering tools and environments enable seamless, trusted collaboration and interactions as part of the digital ecosystem.
- Systems engineering practices are based on accepted theoretical foundations and taught as part of the systems engineering curriculum.
- Systems engineering education is part of the standard engineering curriculum and is supported by a continuous learning environment."[1]

  These challenges or goals require good, solid, systems engineers who can zoom in on the details and zoom out to see the big picture. The need for good systems engineers is ever increasing, due to several concurrent factors [2], [3]:

- Development of Increasingly complex systems in all domains (e.g., medical, energy, aerospace, smart cities, smart agriculture, climate assessment, etc.)
- Rapid pace of technology advancement
- Expanding Digitalization
- Increase in Cyber-Physical systems
- The increasing degree of interconnectedness of the world and the resulting interdependence
- Stressed natural resources
- Increasing amounts of embedded software & applications, large data sets, AI/ML
- Global, thus multi-cultural, projects and stakeholders
- Increasing use of global supply chains
- Systems increasingly Interconnected with other systems as part of larger System of Systems
- Smart systems driving greater need for human-system integration
- Environmental sustainability needs, climate change, efficient resource utilization/reduced waste, clean energy & new sources of energy
- Advances in Materials & Manufacturing
- Advances in Biotechnology

- Increasingly integrated terrestrial & space-based communications technologies
- Increasing use of geospatial technologies & the resulting ethical issues

In this paper, the goals, challenges, and needs are compared to the formal education offered by the top 10 U.S. schools offering systems engineering bachelor's degrees, and a gap assessment is presented.

Sources of Information

In the U.S., the top 10 Bachelor's degree program are offered by the following schools:

1) Washington University in St Louis
2) University of Virginia - Main Campus
3) University of Florida
4) University of Pennsylvania
5) University of Illinois at Urbana-Champaign
6) George Washington University
7) Case Western Reserve
8) University of Arizona
9) George Mason University
10) Kennesaw State University

Note these schools and the ranking was obtained from College Factual 2023 College Data Analytics Team which used the following criteria:

- Early career earnings
- Average SAT/ACT scores of incoming students
- Amount of focus on systems engineering (how many resources a school devotes to systems engineering students as compared to other majors)
- Major demand (How many other systems engineering students want to attend this school to pursue a bachelor's degree)
- Educational Resources (e.g., number of students per instructor)
- Student Debt
- Degree completions (graduation rate)
- Accreditation

This is just one method of ranking and determining the top 10 schools. It can be argued that there could be other or additional relevant criteria, but to facilitate the survey performed in this paper, the author used the rankings presented by College Factual. It is not as important to focus on exact rankings or schools, but to survey the group of schools' systems engineering curricula and determine whether there are gaps in terms of what is provided vs. what is needed to meet INCOSE 2035.

Methodology

A quick review of the curriculum posted by each University on the internet was performed to compare and contrast the undergraduate programs of these top 10 schools and identify gaps.

Note that this review was not an in-depth exploration of each curriculum. For example, the syllabus for each course was not reviewed. The author just used the names of the courses listed on each program's website to make a judgement regarding the intent of each course. Further studies and surveys could investigate each curriculum more in-depth. In addition, a review of the advanced/graduate programs offered by various institutions could be looked at in future reviews.

Findings

It was found that each school's systems engineering program offers the foundation of engineering math, chemistry, and physics. Each program offers systems engineering focus areas such as systems design, systems analysis, and statistics, as well as a set of engineering electives to choose from. Each program requires 120-130 units of credit to complete the degree. However, that is where the commonality ends. Even the set of electives offered varies widely across the programs.   Some programs offer electives in broad categories such project management and thermodynamics, others require electives in certain categories, while others offer very specific/narrow electives such as finite element analysis and Optics and Photonics and Quantum Computing. Some require a capstone senior design project, and others require completion of an internship. One requires identification of a secondary field of study in a selected category such as automotive engineering, autonomous systems and robots, bioengineering, control systems, digital prototyping, or environmental engineering.

Only a few require a course in engineering ethics. Only a few require a technical writing or communications course.

Table 1 shows the systems engineering skills and proficiencies needed by today's and future systems engineers based on INCOSE 2035's vision and future projections, as well as the results of the review performed.

Need	Majority of Programs Meet Need?	Majority of Programs Do Not Meet Need	Comments (# of programs that provide)
Systems Thinking	X		
Engineering Math	X		
Engineering Fundamentals in multiple disciplines (e.g., electrical, mechanical/dynamics, thermodynamics, etc.)	X		
MBSE		X	1 of 10
Simulations		X	3 of 10
Visualization Technologies		X	0 of 10
Multiple Domains		X	2 of 10
AI/ML		X	3 of 10
Data Analytics		X	5 of 10
Multi-Cultural/Working with multiple cultures		X	2 of 10
Human Factors		X	4 of 10
Materials & Manufacturing		X	1 of 10
Exposure to Environmental Engineering		X	1 of 10
Exposure to Biotechnologies		X	1 of 10
Exposure to Sustainability		X	1 of 10
Engineering Ethics		X	3 of 10 programs provide, plus 1 Engineering Law
Ability to lead multi-discipline teams	X		
Ability to write/speak and communicate effectively		X	3 of 10
Knowledge of human dynamics		X	0 of 10
Knowledge Management Strategies		X	0 of 10
Exposure to Industry		X	2 of 10
Agile Development Methodology		X	0 of 10

Table 1: Systems Engineering Needs Vs. Education Offerings by Top 10 Undergraduate SE Schools

As seen in Table 1, the systems engineering curricula being offered by many of today's top undergraduate programs looks to be falling short in terms of laying the groundwork for our up-and-coming systems engineers. It appears that the systems engineering education being offered by many of the undergraduate programs will need to be revamped in order to keep up with the increasing and evolving needs for systems engineers.

Belcan Solution

Belcan, a US company in business since 1958, is a top strategic partner for purchased services, providing $1 billion of Engineering, Technical, and Consulting services annually. Belcan' clients include top OEMs and Tier I supply chains, including manufacturers and system / subsystem providers. Belcan is among the largest engineering companies in the U.S. providing end-to-end engineering services from conceptual design to aftermarket support. The company has multi-industry experience as a global supplier of engineering services. Figure 1 shows some highlights of Belcan.

Figure 1: Belcan Overview

Belcan has a large cadre of systems engineers, supporting multiple clients, domains, and types of programs. As such, it is imperative that the systems engineers possess the skills and proficiencies needed to ensure our customers' success now and in the future. To address this, Belcan has utilized a multi-faceted approach to ensure we employ and field top-notch systems engineers; several initiatives have been put in place.

A 20-course "Systems Engineering Journey" was developed by Belcan systems engineers as a grass-roots project and was posted for use by the company's systems engineers. This SE Journey covers the foundational skills needed by all systems engineers. The Systems Engineering Journey includes:

Course 1-Introduction to Systems Engineering
Course 2-Soliciting & Defining Customer Expectations and Performing Concept Selection
Course 3-Requirements Definition and Management
Course 4-Developing a Systems Architecture
Course 5-Interface Management
Course 6-"V" in V&V
Course 7-Trade Study Methodologies
Course 8-Use of Models and Simulations in Systems Engineering
Course 9-Reliability and Specialty Engineering
Course 10-Configuration Management
Course 11-Implementation
Course 12-Integration
Course 13-Transition
Course 14-Risk and Opportunity Management
Course 15-SE metrics; Lessons Learned vs. Lessons Implemented
Course 16-MBSE Fundamentals
Course 17-System Safety
Course 18-Introduction to Agile Development with Scrum
Course 19-Intro to DevOps
Course 20-Project Management Best Practices

The intent of this training program/journey is to ensure a “level-set” of all Belcan systems engineers, such that a common vocabulary is understood, and that all systems engineers can support any systems engineering tasks/approaches that our customers need at any point and through the full life cycle of a system. All gate reviews, milestones, and deliverables can be supported by our systems engineers.

Belcan has set up a “Belcan University” based on the Percipio platform by Skillsoft. There are over 40,000 courses, videos, and books available across multiple domains for the betterment of our engineers. The courses range from general courses such as project management, general productivity, Diversity/Equity/Inclusion, and Microsoft tools, to specific courses on digital transformation, jet engines, airframes, composites manufacturing, rocket systems, hydraulics, fracture mechanics, DOORS tool, DO-178C, as well as many others. Belcan also hosts “Lunch and Learn” sessions where technical expertise is shared across the company and the presentations are posted on BelcanU for future viewing by anyone in the company. Case studies documenting past project efforts are also prepared and posted for use company-wide, serving as lessons learned for systems engineers performing similar projects and tasks.

Belcan has also set up an intensive MBSE training program, complete with different tracks and credential levels. This MBSE training program prepares engineers to operate in a fully model-based engineering practice and enhances systems engineering, modeling language, architecture development, and simulation skill sets through dedicated instruction, pertinent project assignments (at times with customer participants), and access to multiple vendors’ MBSE tools and resources. The students work in cohort teams with guidance as the training progresses to higher levels. Belcan has also partnered with the University of Michigan and other industry partners to develop, set up, and use a MBSE lab. This MBSE Lab at University of Michigan is a first-of-its-kind program that provides a teaming and collaboration space where students participate in Belcan and other industry partners'-sponsored projects to design, build, test, and fly aircraft using MBSE and industry-proven SE tools, approaches, and processes. Belcan is one of the active partners in the MBSE Lab, which fosters innovation in the fields of systems engineering and advanced technologies, benefitting both Belcan and future systems engineers. For more information about this MBSE lab, please go to this link: https://aero.engin.umich.edu/undergraduate/program-overview/mbse-at-u-m/. Belcan has also set up an Innovation Hub, which includes participation from members of industry.

Belcan has a robust internship program, as well as an innovative Academics-To-Industry (A2I) program. Belcan also promotes the study of Science, Technology, Engineering, and Math (STEM) to help shape and empower the next generation of problem solvers and engineers. The Belcan STEM program is backed by resources across the company and is very active within our various communities.

This collective set of approaches to systems engineering skills enhancement, for both future systems engineers and current Belcan engineers ensures that Belcan hires, engages, and fields systems engineers with the skills necessary to meet current and future needs. Systems Engineering education and continued skill growth and development opportunities provided by Belcan are consistent with supporting the objectives of INCOSE's Systems Engineering Vision 2035. Table 2 shows the same needs as presented in Table 1, but this time with the Belcan offerings shown.

Need	Belcan Provides Education/Support?	Belcan Offering
Systems Thinking	X	Systems Engineering Journey
Engineering Math		Graduates have already before incoming to Belcan
Engineering Fundamentals in multiple disciplines (e.g., electrical, mechanical/dynamics, thermodynamics, etc.)	X	Belcan University
MBSE	X	MBSE training program, MBSE lab
Simulations	X	Systems Engineering Journey, MBSE training program, MBSE lab
Visualization Technologies	X	Belcan University
Multiple Domains	X	Lunch and Learn, Belcan University, Case Studies

AI/ML	X	Lunch and Learn, Belcan University
Data Analytics	X	Belcan University
Multi-Cultural/Working with multiple cultures	X	Belcan University
Human Factors	X	Lunch and Learn, Belcan University
Materials & Manufacturing	X	Lunch and Learn, Belcan University
Exposure to Environmental Engineering	X	Belcan University
Exposure to Biotechnologies	X	Belcan University
Exposure to Sustainability	X	Belcan University
Engineering Ethics	X	Required Annual Training
Ability to lead multi-discipline teams	X	Systems Engineering Journey, Belcan University
Ability to write/speak and communicate effectively	X	Belcan University
Knowledge of human dynamics	X	Belcan University
Knowledge Management Strategies	X	Case Studies, Innovation Hub Belcan University
Exposure to Industry	X	By virtue of the business that Belcan conducts
Agile Development Methodology	X	Systems Engineering Journey, Belcan University

Table 2: Belcan Offerings to Meet Needs

Summary

The review performed in this paper used a curriculum-based approach to compare the INCOSE Vision 2035 with the undergraduate programs of the top 10 U.S. systems engineering programs. Future investigations could include expanding the review to include international programs and Graduate programs. In addition, different methodologies could be used to compare programs. For example, a deeper dive could be performed by interviewing systems engineering programs' faculty, interviewing current students and graduates, and interviewing the employers of graduates to get a measure of success from which to compare.

The review and analysis performed in this simple, exploratory study shows that the systems engineering curricula being offered by many of today's top undergraduate programs will not meet the needs of the goals and objectives laid out in INCOSE's Vision 2035. It would serve the systems engineering community and education community well to consider updating and revamping these undergraduate programs to be more aligned with this vision. Industry should also consider putting in place development programs and strategic partnerships to further enhance systems engineers' education and development, and to ensure systems engineers get to and stay on the leading edge of the advances in technology, systems, methodologies, and tools.

Acknowledgement

The Systems Engineering Vision 2035 is Copyright © 2021 by INCOSE

About the Author

Robin Rose has 36 years of systems engineering experience on space, military, defense, and commercial aircraft programs, managing complex programs, and managing complex requirements. She possesses a diverse set of systems engineering and project engineering skills, covering the complete product development, V&V, and operations life cycle. After 24 years at Boeing, she worked for 8 years at B/E Aerospace (Collins Aerospace) and joined Belcan as an advisory consultant in 2019.

References

1 *Systems Engineering Vision 2035* Copyright © 2021 by INCOSE
2 *Future of Systems Engineering (FUSE)*, International Council on Systems Engineering, 2022
3 W.D. Miller, "The Future of Systems Engineering: Realizing the Systems Engineering Vision 2035", *Transdisciplinary and The Future of Engineering*, October 2022

Growing your own Systems Engineers: the case of TMC Italia

by Dr. David Ward, ~~PhD~~Ph.D., ESEP (TMC Italy SE Consultant)
Ing. Antonio Abadessa (TMC Italy Managing Director)

Abstract

Second only to the challenge of developing and deploying a systems engineering (SE) competency is finding systems engineers (S_{Eng}) to carry out the relevant work while growing in knowledge and SE stature. The case of TMC Italy is therefore not an exception rather the rule but how it is going about doing it and possibly proposing it as a model for others, is the attractiveness and originality of this brief account.
The authors set-out to illustrate and provide some of the details and highlights of developing a SE competency through an ad hoc education and training program. More specifically they discuss a four-phase training process, and ~~describe~~ describe some of the novel methods/tools developed while blending~~blend~~ hard/soft skills with traits. Insights into developing and deploying a SE mindset as well as learning how to grow one's own systems engineers is also provided.

Introduction and Overview

Almost every engineer we~~I~~ have met in almost 50 years of work were taught and brought up as systematic thinkers, including the authors. This derives from the schooling and training received and is a consequence of the delivery of knowledge and thinking received from others, especially their (systematic thinking) teachers/lecturers/trainers. Even peers and bosses apply the same systematic mindset in everything from problem solving to performance appraisal. In other words, education and training, is almost entirely geared for systematic thinking.
In short, the educational system mass-produces systematic thinking engineers and not systemic thinking engineers and only in specific circumstances do we hear of systems thinking [1]. Simultaneously the same educational system produces workers rather than entrepreneurs. Those same workers become 'knowledge workers' and perhaps subsequently 'decision makers' rising from lower ranks to higher ones such as managers. We shouldn't be surprised that many of the greatest innovators and entrepreneurs were rejects from their respective educational system.
This implies we 'engineer' the solution provider to solve the problem rather than help see the big picture and the business opportunity that stems from the business problem. Elon Musk put it very well *"Possibly the most common error of a smart engineer is to optimize a thing that should not exist."* [2]
But things are changing, mainly because complexity has reached such levels that systematic thinking isn't enough and may even be a key reason why complex systems fail. Thus, the rise of systems engineering, and the desperate demand for systems engineers and discovering the need to educate and train the engineers we have.
TMC is fortunate because its *employeneurship* business model [3] is a combination of employee-entrepreneurship and includes among other things individual profit sharing and individual coaching. With dedicated SE training the engineers at TMC reap the benefits of systematic thinking while seeding systemic thinking.
From the outset of the SE Personal Development (SEPD) program in 2020 TMC decided to build a mindset and not just educate/train engineers. The message was 'grow our own systems engineers', combining skills and traits.

Kick-starting the Program

The SEPD program was kick started following four steps:

1. Assessment of SE needs and expectations of the TMC customer base, especially from a skills and traits viewpoint, and how these link to TMC's five pillars of employeneurship (Business Cells, Individual Profit Sharing, Long-Term Working Relationship, The Entrepreneurial Lab and YOUniversity-Coaching).
2. Establish the skills and traits of the SEPD program trainees and how they compare to step 1. This also included aspects such as age, specialization, experience, current and past projects.
3. Estimate SEPD program investments and costs e.g., purchase of SE standards, INCOSE training material and media etc.
4. Preparation of SEPD program roadmaps.

Hard/Soft skills versus Traits schools of thought

Hiring and training in enterprises are heavily focused on either hard or skills or both. However, from experience we know that although skills are crucial to carry out tasks it is how these tasks are tackled (especially with others involved) that often dictates their success or failure. Simplifying, skills are about the 'what' while the 'how' is about the traits that the individual exploits to carry out the tasks. Further, skills link to responsibility while traits connect to accountability irrespective of task, role and/or challenge.
Interestingly when enterprises move to traits the 'how' moves away from satisfying tasks to providing results i.e., deliverables. It is here what the value of traits and characteristics of the individual surface, and it is especially true when the challenges are complex, full of uncertainty and systemic.
Ironically during hiring or when establishing subsequent training strategies performance and skills dominate relegating or neglecting traits. Manager driven organizations favour skills while their leader equivalent favours first traits and only after skills. Balancing skills and traits is not easy, also because many don't know the difference and/or how to pick-up and measure their value.
A quick look at the next table of examples will help clarify and perhaps aid in finding the right mix:

Hard Skills	Soft Skills	Traits	
Are about the technical knowledge the person has gained through academic and professional training and/or working experience.	Are about the habits and behaviours of the person often inspired by circumstances.	Are about distinguishing qualities or characteristics, personality features of the person. Many are tied to upbringing and family education.	
○ Academic specialization such as Mech. Engineering ○ Foreign Languages ○ Coding/Programming Languages ○ SEP Certification ○ Design e.g., CAD, CFD, MBSE	○ Communication ○ Teamwork ○ Problem-solving ○ Critical thinking ○ Time management ○ Conflict management ○ Negotiation	Lighter: ○ Integrity ○ Loyalty ○ Devotion ○ Kindness ○ Sincerity ○ Patience ○ Resourceful	Heavier: ○ Confidence ○ Determination ○ Charisma ○ Authority ○ Enthusiasm ○ Risk taking ○ Ownership
Often linked to active learning	Often linked to the behavioural learning	Traits are split into 3 categories: a). Cardinal, form your recognition b). Central, form your core customs c). Secondary, are your preferences	

The SEPD program combines the skills and traits schools of thought as follows:

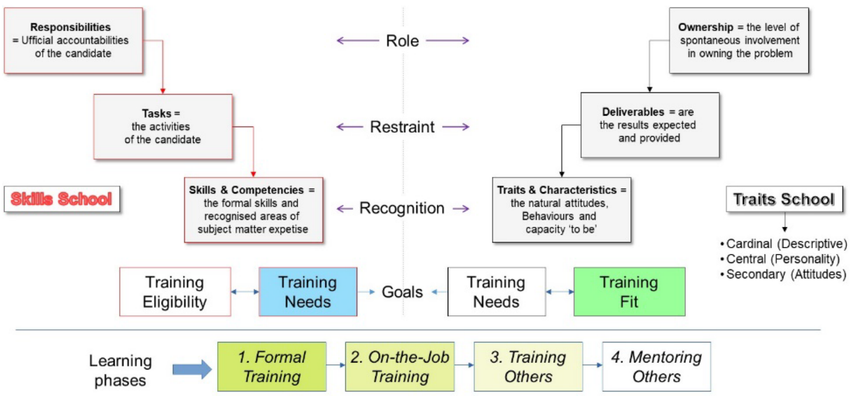


Figure 1 – Skills and Traits schools of thought in the SEPD program

The program is designed to provide systems engineering skills while building an awareness of the trainee's traits through four learning phases and roadmaps.

The 4-phase SEPD deployment process

Trainee personal development starts with formal module-driven training then applying this knowledge in the workplace. Subsequently the trainee transfers the knowledge and experience gained to peers and subordinates and concludes mentoring others to do the same.

Figure 2 – 4-step SE Personal Development program

During phase 1 the trainees are exposed to a very broad but detailed view of SE with progressive learning challenges. In this formal training phase such SE learning is split into three parts: 1.preparatory, 2.pillars and 3.specifics ending with the option to go for SEP certification [4]. A piece-wise view of the modules provides the first roadmap:

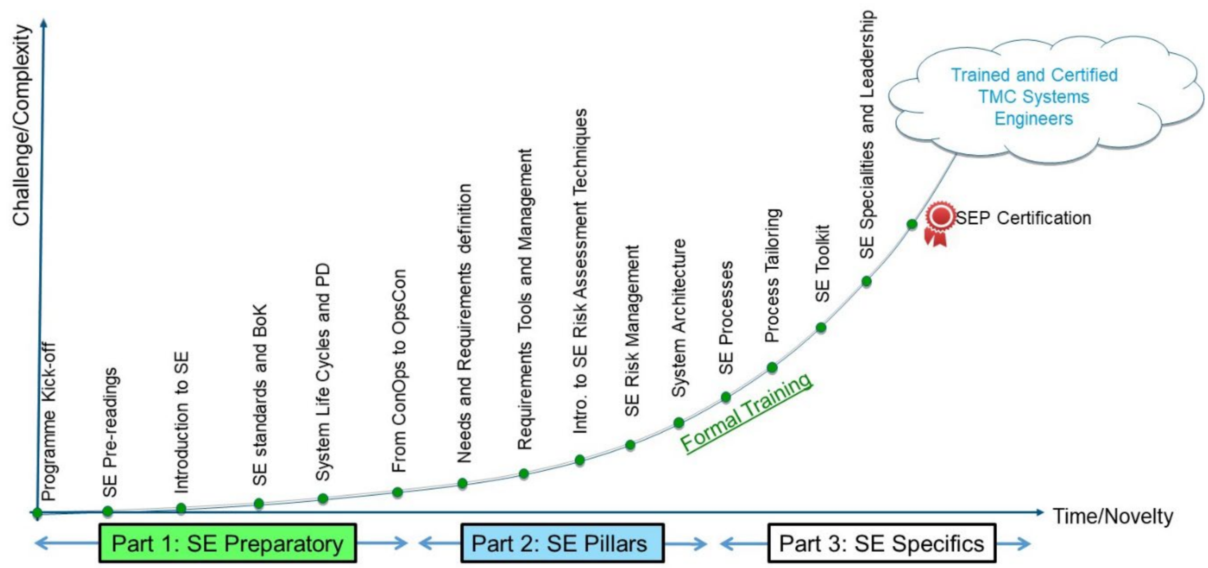


Figure 3 – Step 1 Formal Training Roadmap

Idea Generation as a Training tool and learning the art of Architecting

To fortify SE concepts during part 1 each trainee ideates an idea concerning a system (product or service) and answer 4 fundamental questions:

1. What is your idea?
2. Who is it for?
3. ~~1.~~3. How will you make money from it?
4. Why is it needed?

Each trainee then presents his/her idea to the rest of the class using an elevator speech [5] approach and subsequently the class votes anonymously through a dedicated on-line questionnaire. The results are then shared and each **ideator** can propose modifications, updates or just simple park/abandon his/her idea.

A key feature of this training approach is to learn to 'architect' the system very early in the system life cycle and listen to potential 'customer' insight. It mixes early business and technical acumen together with fostering a sense of *employeneurship*. It also fosters the importance of user, user flow, user journey and user studies, all crucial to successful SE. Moreover, it highlights the importance of business, stakeholder and system requirements and business risk and deciding on whether to kill or nurture the idea. It may also seed the TMC business cell and entrepreneurial lab pillars and go towards building a mindset.

Product Breakdown as an Active Learning Tool and as an art of Reverse Architecting

Product breakdowns are not new in industry and are often used in cases like bench marking, reverse engineering, cost estimates, assembly assessments, system architecture analysis etc.

So, in the SEPD program, each trainee is required to choose a product that can be disassembled and reassembled manually with simple tools e.g., a screwdriver and thus learn from it. The product chosen must have a minimum number of 5 parts and such as pen drives, Bic® pens, perfume bottles, electric

razors etc. Then in group sessions each trainee disassembles their chosen product and asked to describe the resulting 'architecture' using, for example, box diagrams, pictures, conceptual mapping. The exercise includes other information useful to understand the design choices made by the originator e.g., chip ID, chip manufacturer, type of plastic, plastic and metal parts and relevant tooling, batteries, snap fits, screw sizes and types etc.
The trainee is then solicited to take different system viewpoints and by doing so acquire a better understanding of the system of interest (SoI).

SE Clinic and TMC 'G' guides

As trainees learn the SE basics many doubts surface. These can be derived from their projects, some from experience (or lack of it) and some due to the need to personalise solutions and so forth. To this end the 'SE clinic' provides a sort of one-stop consultancy where trainees can pose specific SE questions. A further learning tool are quick references known as TMC 'G' guides that tackle specific SE topics. Trainees are invited to co-author with the trainer or write their own SE guides.

Aligning Learning modes with modern delivery tools

Since everyone has one or more preferred learning modes, the SEPD program leverages exercises based on the following learning/learner modes [6]:

Behaviourist 1	Provoking reactions from trainees and detecting any changes in behaviour. Thus invoking a reaction and alteration of behaviour.
Cognitive 2	Stoking different kinds of memories, motivation, and thinking to build patterns. It includes social and cognitive behaviour learning.
Constructivist 3	Interpretation and encoding the information based on personal perception and experiences. Learners analyse, rationalize, synthesize, and develop new ideas or tweak old ones through the filter of their own experiences.
Active 4	Learners are actively engaged or involved in the learning procedure to learn better. Interactivities, assembly-disassembly of products, exercises etc. are crucial learning elements.

Another challenge is establishing the most viable trainee learning-delivery approach. Due to the geographic dispersion of TMC trainees this has had to be virtual learning. However, it is suggested that the classroom learning should be promoted first as it leverages all four learning modes [6] and lessens the burden on developing ad hoc training methods/tools.

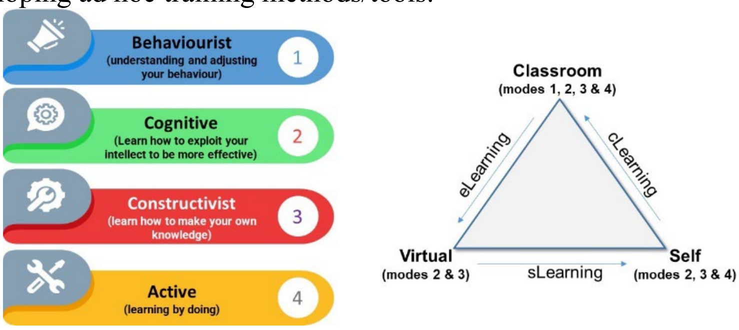


Figure 4 – Learning approach and Delivery

Where does SySTEAM come into play?

Since the early 90s INCOSE is at the forefront in promoting a systems engineering culture including its SEP certification program (early 2000) and more recently through the SySTEAM initiative [7].
The number of SEP certified engineers available worldwide is just ~4200 [4], and totally insufficient with respect to the needs of industry and society.

Interestingly while the number of INCOSE members in Italy is ~210, almost 60% of these engineers are SEP certified compared to ~20% for INCOSE membership worldwide.
All the SEPD program trainees have a strong STEM background but none of them have specific SE training or have a SE educational background. Indeed, the SEPD aims to cover this gap in knowledge. This is first due to a lack of SySTEAM offerings across the whole educational spectrum in Italy. Second, the role of the S_{Eng} is rather recent in Italian enterprises (last decade or so) and currently focused on high-tech sectors e.g., defence.
The only true option left to enterprises is to educate, train and certify the engineers in the workplace. For this reason, TMC's SEPD program is necessarily based on the INCOSE handbook and SEBoK [8].

Conclusions

Educating, training and certifying engineers in the field of systems engineering is a challenge that many enterprises face. But the dilemma of farming them from competitors or growing their own is not a trivial one.
SySTEAM is more than a logical conclusion and response to this evident gap but it needs to span the entire educational system and beyond. The urgency dictates at least two angles of attack, during schooling and in the workplace.
To this end TMC Italy has decided to grow its own systems engineers, aligning this decision with its employeneurship business model while fostering both skills and traits. It has decided to do this through a dedicated and original program that mixes education with training capturing also the attention of its customers. It is a medium to long-term investment until the educational system is capable of supplying engineers with the necessary systems engineering knowledge.

Bibliography

[1] B. Fuller and H. Kim, "Systems Thinking to Transform Schools Identifying Levers that Lift Educational Quality," Brookings, Washington, 2022.

[2] E. Musk, Interviewee, *Iteration and SpaceX.* [Interview]. August 2021.

[3] TMC, "Employeneurship," 2023. [Online]. Available: https://tmc-employeneurship.com/employeneurship. [Accessed July 2023].

[4] INCOSE, "Systems Engineering Certification," 2023. [Online]. Available: https://www.incose.org/systems-engineering-certification/certification. [Accessed July 2023].

[5] T. L. Sjodin, Small message, big impact: the elevator speech effect, Penguin, 2012.

[6] Hasan and Rahman, "Active Learning Framework and Process of Classroom Engagement: A Literature Review," *International Journal of Trend in Scientific Research and Development,* vol. 6, no. 5, pp. 1109-1117, August 2022.

[7] INCOSE, "SySTEAM Initiative," INCOSE, 2021. [Online]. Available: https://www.incose.org/2023_redesign/communities/working-groups-initiatiaves/systeam-initiative. [Accessed July 2023].

[8] INCOSE, IEEE, Stevens Inst., "Guide to the Systems Engineering Body of Knowledge (SEBoK)," 2023. [Online]. Available: https://sebokwiki.org/wiki/Guide_to_the_Systems_Engineering_Body_of_Knowledge_(SEBoK). [Accessed July 2023].

Using A3 Architecture Overviews as an educational tool
Educating new artists in Systems Architecting

Steven P. Haveman[1*], Bauke Steenhuisen[1], G. Maarten Bonnema[2]
[1] Institute of Design and Engineering, HU University of Applied Sciences Utrecht, Padualaan 99, 3584 CH Utrecht, The Netherlands

[2]Chair of Systems Engineering and Multidisciplinary Design, Department of Design, Production and Management, Faculty of Engineering Technology, University of Twente, P.O. Box 217, NL-7500 AE Enschede, The Netherlands

[*] Corresponding author: steven.haveman@hu.nl

Abstract

To successfully develop a system, a solid understanding of its architecture by stakeholders involved in the development of the system is key. This process is supported by System Architects, who have a profession that is often regarded as experience based. However, we argue that it is important to familiarize students with the concept of System Architecting, so that they are at least receptive of the nuances involved and potentially can continue a pathway of development towards such a role. In this paper we explore the potential use of A3 Architecture Overviews (A3AO) as an educational tool to support familiarization with Systems Engineering and Systems Architecting. The A3AO has been developed as a supportive tool to communicate a system's architecture. It uses diagrams to model and visualize a system with different views and is intended to be printed on a physical A3 paper. It serves as a reference for, and facilitator of design discussions. Skills envisioned to be developed while using an A3AO include strict selection and visualization of information, two critical competencies to handle systems' complexity. The A3AOs have been applied in a course on Systems Engineering at an applied University in The Netherlands and were part of the assessed deliverables. The relative free-form nature of the A3AO posed students with various dilemmas in their use, but also provided the opportunity for guided development on the envisioned competencies. We conclude that more research is required to further formalize this guided development, but we also experience that the A3AO has the potential to support systems engineering and systems architecting practices in education.

1. Introduction

In the past decades, society and its supporting systems have been transitioning to an increasingly connected and digital world. This pace is only accelerating. For engineers or other developers, this means that more and more, they must design their products considering the wider context of that product, and not consider them as products but as systems. To handle complexity, an engineer should scope development towards a specific system-of-interest. However, scoping already implies that the system-of-interest is part of a larger system. Therefore, an engineer should consider both the influence of the wider context on the system-of-interest, as well as the impact of the system-of-interest on its context.

The domain of Systems Engineering offers processes, tools and ways of thinking (Bonnema, Veenvliet, and Broenink 2016) that support the development of such systems. The more strategic and holistic side of the Systems Engineering approach is often called Systems

Architecting. In this context, the architecting approach has been referred to as an art (Maier and Rechtin 2009). The earlier described societal need for systemic solutions prompts an increasing need for professionals that can address this need. Ultimately, this begs the question how to educate new artists in Systems Architecting. We explore this question in the context of a Master program at the HU University of Applied Sciences Utrecht in the Netherlands.

The paper aims to answer the posed question as follows. Firstly, by discussing the background of systems architecting and their education in section 2. Secondly, by introducing a tool – A3 Architecture Overviews (A3AOs) that may contribute to this education in section 3. An exploratory case study utilizing the A3AOs is presented in section 4. Finally, the outcomes of the case study are discussed in section 5. An outlook for future work is presented in section 6.

2. Teaching Systems Architecting

This section discusses key aspects of Systems Architecting in an educational context. Already at the early days of Systems Engineering, the comparison to Architecture was identified. Bode (1967) is paraphrased by SEBOK in a brief history on Systems Engineering (SEBOK 2023a):

> *"…the systems engineer resembles an architect, ... Like architecture, systems engineering is in some ways an art as well as a branch of engineering. Thus, aesthetic criteria are appropriate for it also. For example, such essentially aesthetic ideas as balance, proportion, proper relation of means to ends, and economy of means are all relevant in a systems-engineering discussion. Many of these ideas develop best through experience. They are among the reasons why an exact definition of systems engineering is so elusive."*

Within the ISO/IEC/IEEE 42010 (ISO/IEC/IEEE 2011), the following definition is offered for a system architecture:

> *"fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution"*

The ISO/IEC/IEEE 42010 definition shares some overlap with the definition in SEBOK (SEBOK 2023c). In the above views on Systems Architecting we see terms such as "global", "high-level structure" and "fundamental concepts" that are derived from the "properties", "relationships" and "elements" of a system in such a way that "balance" and "proportion" are maintained. Going forward in this section we will discuss the core qualities expected from a systems architect and how to address this in an educational context.

2.1. Core Competencies of a Systems Architect

In educating systems architecting, the students should be familiar with the way of working and competences of a systems engineer. One can take inspiration for this from for instance (Bonnema, Lutters-Weustink, and van Houten 2005; Bonnema, Lutters-Weustink, and Jauregui-Becker 2016) and (Muller and Bonnema 2013). Based on the definitions offered above, and for example the work of (Maier and Rechtin 2009) and (Muller 2011), we can derive additional relevant activities central to the System Architecting process, and from those derive relevant competencies for a systems architect.

In principle, a System Architect has a visionary and strategic role with a systems' development, or even across the development of multiple systems (Muller 2011). To support this role, we would like to highlight two competencies. In this, we acknowledge that we are by no means exhaustive or complete in the competencies we present.

The first competence to highlight relates to finding the “fundamental” aspects of a system. This means that given the topic at hand, a System Architect should excel at critical information selection, or to *be able to capture the essence of a system*. This includes interacting with a wide variety of stakeholders, being able to ask the right questions and scan information quickly. It also involves being able to reason in a more functional manner, which allows one to focus on the purpose of a system.

Secondly, the results are then to be communicated across stakeholders (which can occur simultaneously with the capturing process). To support this, a System Architect should *be able to visualize and communicate the essence of a system* appropriately. Multiple approaches can be used here, for example facilitating a common language (e.g. through SySML) is one, but it can also be done through less formal means (Muller 2011). The end goal is to facilitate a shared view on the system.

In principle, (Maier and Rechtin 2009, p274) state in their guidance on curriculum design that Systems Architecting is primarily inductive and heuristic based, whereas other engineering course are more deductive. In this, there is another competence to be found, which is to act on heuristics (Maier and Rechtin 2009). We argue that this competence exemplifies why System Architecting is often regarded as an experience-based profession.

The question then becomes where to start with junior “product” engineers that are novices in system development. In our view, Systems Engineering and Architecting education gives counterweight to the usual engineering educational flow of focussing on ever more precise details to ever more depth. If one wants to educate future systems engineers and architects, the first step is to make students aware of the profession of a Systems Engineer/Architect (SE/A). Some students will want to learn more, and potentially develop into full systems engineers or architects. The two competencies “be able to capture the essence of a system” and “be able to visualize and communicate the essence of a system” we presented are, in our view, ideal starting points for students to exercise and experiment with.

3. A3 Architecture Overviews

This section presents the A3 Architecture Overview and will discuss its conception and why we consider this a potentially natural fit in education.

3.1. A short history

A3AOs were conceived as the result of the work of (Borches 2010). Borches was looking for a way to support evolvability in high-tech systems. After an extensive exploration he concluded that the problem was not so much the inability of engineers to estimate the impact of change, but the lack of shared understanding of the system and its architecture. He therefore developed a way to reverse engineer (often implicit) architectural information of a system to support product evolution. This resulted in the A3 Architecture Overview, as depicted in Figure 1. As stated by Borches, its design is based on experiences with existing models (including e.g. SySML), tools, and human and organizational factors. The aim is not to be complete, formal, or executable. Instead, the aim is to support effective communication of architecture knowledge. This is done by using non-formal models to discuss a specific (aspect) of a system in interlinked functional, physical and quantification views, supported by visual aids and other views where appropriate. Furthermore, the visuals provide links between the information in the different views, e.g. by indicating which main concerns or requirements apply to which aspects in the specific views. These views are captured on the model side, whereas the summary side provides supporting rationale and further context.

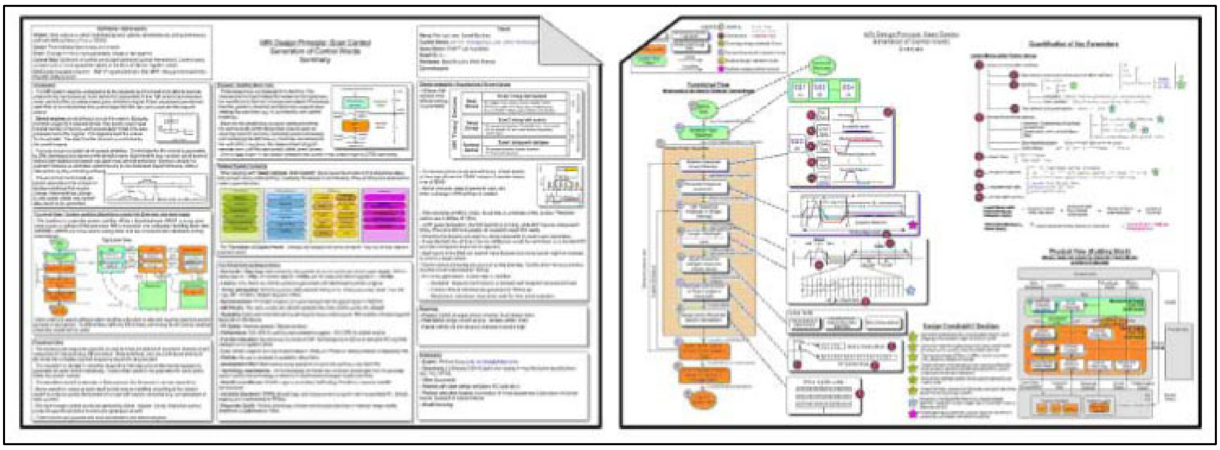


Figure 1 – A3 Architecture Overview example – Left: A3 Summary, Right: A3 Model (Borches 2010) *(rendered unreadable for confidentiality reasons).*

The A3AOs have been implemented in various industries such as healthcare and the oil and gas industry (Kooistra, Bonnema, and Skowronek 2012; Singh and Muller 2013; Wiulsrød, Muller, and Pennotti 2011), and different methodological approaches have also been explored[1]. These approaches range from supporting new product development (Hooft et al. 2020) introducing interactivity (Brussel and Bonnema 2015) and incorporating A3AOs in the communication of simulation studies (Haveman and Bonnema 2016).

Concluding, an A3AO captures interconnected key pieces of information from different viewpoints on a single piece of A3 paper to present and discuss the essence of a system on a specific topic. Due to its paper-based nature, the A3AO is particularly suited for traditional face-to-face meetings and for personal reference.

3.2. The A3AO – a natural fit in education?

The A3AO is (as is the case for systems engineering and architecting in general) directed towards the whole, instead of to the details. It can therefore be used as facilitation medium in first contact with the profession of an SE/A. Because of the hard limitations of (two sides of) an A3 paper, students are forced to decide on the relevance for the system design of every piece of information. At the same time, the format of the A3AO with its three main views, and headings on the text side, helps students in this effort. Already the exercise of making a functional view in addition to the mostly preferred physical view helps students to explore both the solution and the problem domain (Bonnema, Veenvliet, and Broenink 2016). Identifying and quantifying key parameters (also called system aspects, key drivers) is a second important exercise to understand the job of an SE/A.

From a didactic perspective, one could paraphrase the A3AO as easy to learn but hard to master. The iterative process of developing an A3AO (Borches 2010) supports a process of refinement

[1] For more information, see also http://www.a3ao.eu/

and continuous learning. We also pose that the visual style of the A3AO can be regarded as more attractive to prospective students compared to alternatives.

Based on the above, we believe the A3AOs are well suited in an educational setting. In the remainder of the paper, we discuss the application of A3AOs in education and explore the question "Can the A3AO method serve as a supportive educational tool to introduce students to systems architecting?"

4. Exploratory Case Study

In this section we will discuss an exploratory case study where the A3AO is used in an educational setting. We refer to this case study as exploratory since it was not designed as an educational experiment upfront. Nonetheless, we report on the designed educational approach, and we reflect on our and the students' experiences in this course.

4.1. Setting

Our case study is situated in an educational programme at the HU University of Applied Sciences Utrecht in the Netherlands. The case study was executed in the master's program Next Level Engineering (MNLE). The MNLE program is a 1 year, 60EC, full-time program aimed at engineers with a bachelor's degree. The program widens the scope of the often still mono-disciplinary engineers with a systems perspective, data science techniques and offers perspectives on organizational change. A Systems Engineering course (5EC) in which this case study is executed runs in the first quartile of the curriculum. Adjacent to this course, the students also work on an Interdisciplinary Project. The Systems Engineering course makes use of that project to apply SE techniques and methods directly to the running cases in the project.

The Systems Engineering course has two intended learning outcomes, of which one is specifically linked to the use of A3AOs. This has the following definition:

> *After completing the course, the student demonstrates the ability to analyse, design and improve complex systems, components and / or processes to meet the specified needs with respect to realistic constraints from an economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability point of view.*

Translated shortly we communicate this as "The student has hands-on experience with Systems Engineering and is comfortable in applying it in a design process". To structure the course in a few thematic sessions, the course was designed around three phases or focus areas, overlayed on the Vee-model, as can be seen in Figure 2

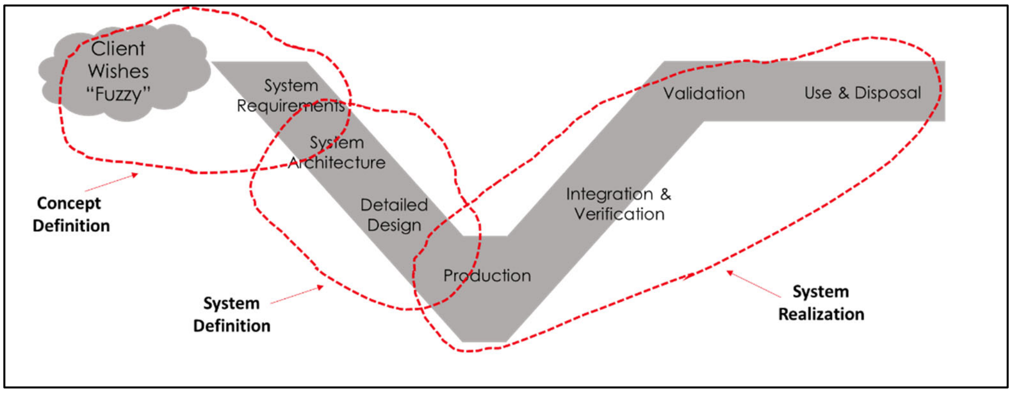


Figure 2 – Focus Areas (Concept Definition, System Definition, System Realization) within the Systems Engineering course

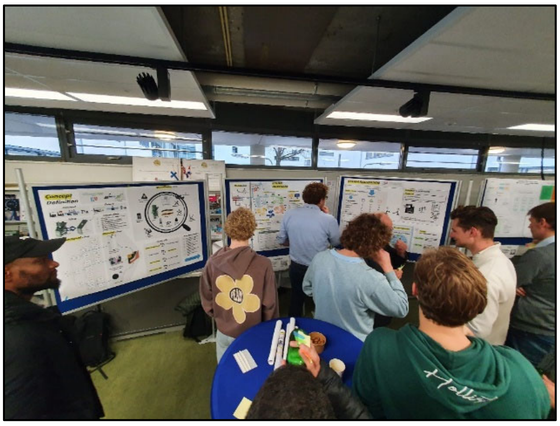


Figure 3 – Poster Market with enlarged A3AOs

The specific assignment that was asked to the students was to create three SE posters[2] based on the A3AO style, one for each focus area. These posters, or A3AOs, were also required to facilitate a design discussion. The content of the posters was linked to the projects the students were executing in the parallel course "Interdisciplinary Projects". A full description of the assignment can be found in Appendix I. The final assessment for this assignment was a group interview in a meeting setting – the examiners and students sat around a table and discussed the printed A3AOs in the middle of the table. The assessment rubric used can be found in Appendix II. Furthermore, a set of questions was prepared for the examiners and can be found in Appendix III –these questions focus on the use of the tool, rather than on the presented results in the A3AOs. It should be noted that at that point in time, the running projects were only halfway through – the projects themselves last one semester.

To conclude the course, the A3AOs were printed enlarged and demonstrated to a wide audience (of students in other programmes, teachers, project clients and others) in an informal poster market setting, see Figure 3. This last activity was not part of a formal assessment for the course results.

4.2. Results

Three groups of five or six students executed the assignment. The groups were working on three separate projects in the healthcare and energy domains. The educational and cultural background of the students was diverse (but limited to the engineering domain). Each group of students delivered a set of three A3AOs as requested in the assignment, one for each focus area (see Figure 2). We report on three aspects of the study, being the process, the results and the outcomes of an evaluation.

The assignment was introduced in detail halfway through the course and from that point a weekly returning topic in tutorials where we would discuss draft versions with the students. In this, students were logically starting with a blank canvas and filling it step-by-step. We encouraged students to utilize the A3AOs in design discussions with stakeholders in their projects, but we also observed that students seemingly lacked enthusiasm or incentives to do so.

[2] We made a subjective choice to present the concept to student as posters, in this paper we aim to consistently use A3AOs if applicable to refer to the created artifacts.

Towards the end of the course, the A3AOs were finalized by all groups and submitted for the assessment. Three of the results are shared in Figure 4, Figure 5 and Figure 6. In the assessment, the examiners (two of the authors) focused on the model sides and discussed with the groups what each model side brought or could bring to the design process. The rationale on the summary side of the A3AO was regarded by the examiners mainly as preparatory work by students for the discussions in the assessment. In the end all groups passed the course. For each group, we present a few of our remarks

- Group 1, this group managed to provide the different views as requested but lacked a clear scope in their A3AOs. In Figure 4, their "concept definition" A3AO is depicted. It aims to present different kinds of concepts for interactivity and links this choice across different views. After discussion in the examination, this poster was assessed to lack some crucial details, so in that sense, the overview was incomplete. A further observation is that the visual style used for the context diagram is perhaps too ambiguous, which is an inherent risk of using an informal modelling approach.
- Group 2, this group focused very heavily on a graphical and storyline approach for their A3AOs. In this, they presented a clear story but lost some of the Systems Engineering approach. An example can be seen in Figure 5 which discussed the "system definition". Here a functional block diagram, an N2 diagram and requirements can be recognized. However, the remaining content is a bit unstructured – other tools could have been applied.
- Group 3, this final group admirably struck a nice balance between "SE-language" and an attractive visual style, as shown in Figure 6. The wall visual itself is a nice touch since the project was about house renovations. The system interactions might be hard to read but were an admirable effort to transform an N2 diagram into a more compact style.

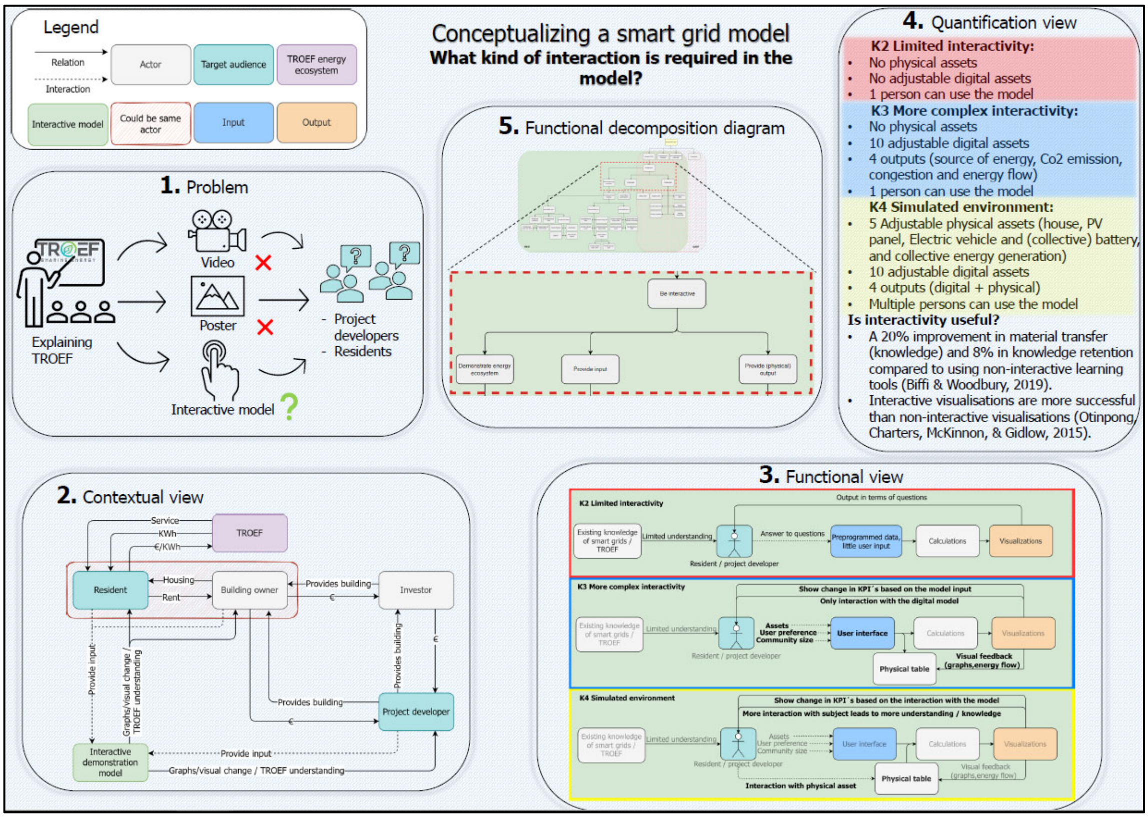


Figure 4 – Concept Definition A3AO Model Side of Group 1

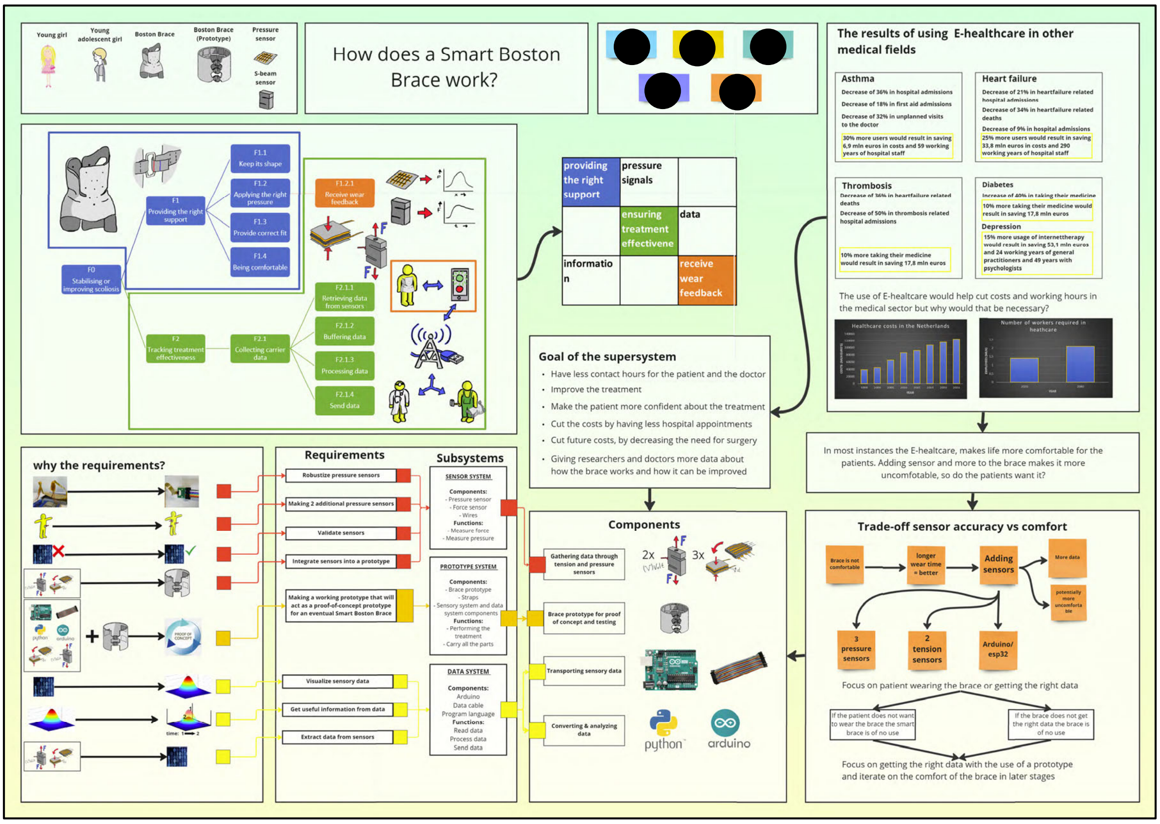


Figure 5 – System Definition A3AO Model Side of Group 2 (names of group members are hidden with black dots)

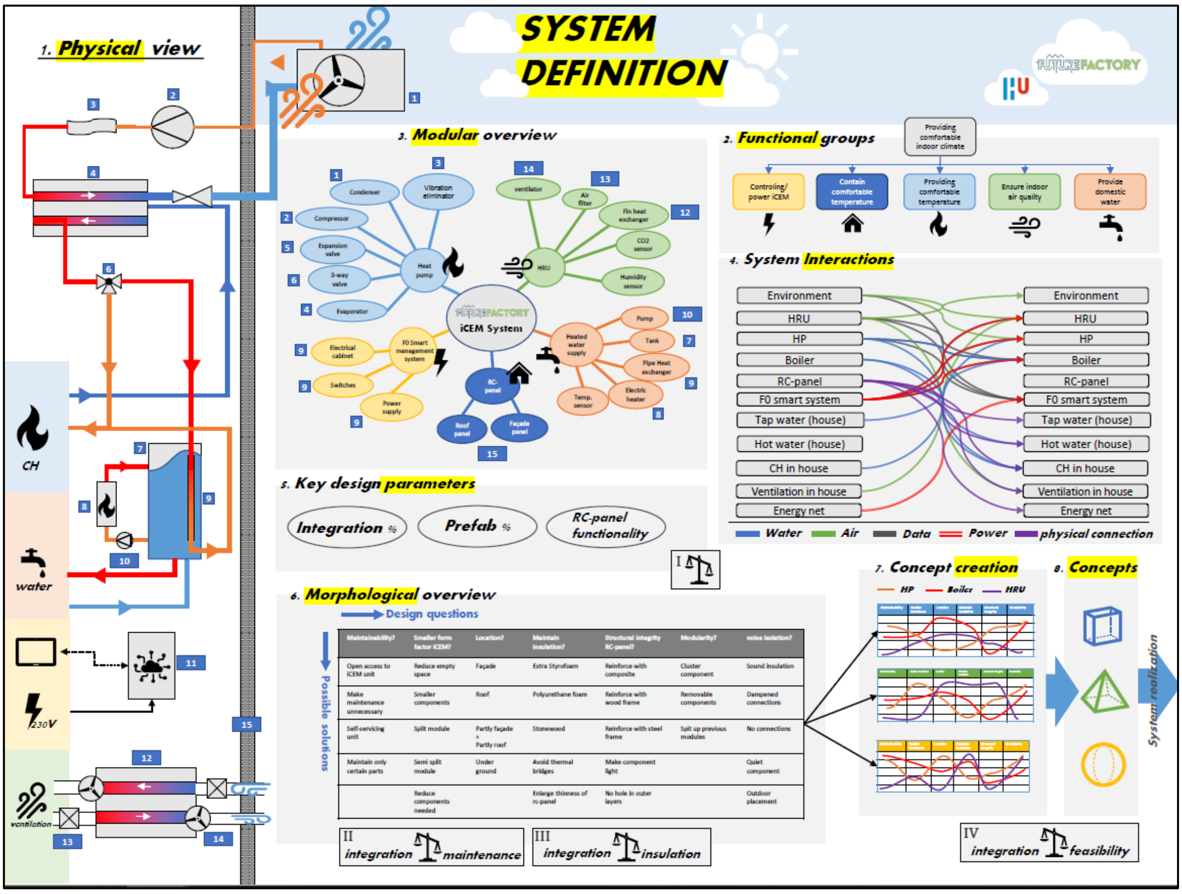


Figure 6 – System Definition A3AO Model Side of Group 3

The course and application of the A3AOs were evaluated by discussions between students and teaching team, a survey and two in-depth interviews. All these evaluations were not specifically focused on the A3AOs but when analysed, provide a few points of feedback.

- We start with seemingly the worst feedback at face value. In one course evaluation a student stated "I though the example poster was very ugly. If I would encounter this at a company, I could not take this company seriously".
- More feedback was offered by the same student, which was also supported by other students in discussions. This feedback centred on the fact that "the posters were a lot of work for information that was already known".
- The two in-depth interviews revealed the working process for two of the groups. In a project setting students will naturally divide the work between them. This had as consequence that in those groups the posters had one main author with other students in a supporting role, sometimes very limited.

5. Discussion

In this section we reflect on our own experiences and particularly the final points of feedback presented in the case study results.

In our view, the greatest strength of the A3AO is also its greatest weakness: anything goes. The tool can be used for many goals, many audiences (internal, external) and in many development phases or contexts. This apparent Swiss-army knife quality is both an opportunity and a threat. Overall, we have perceived the A3AO approach as beneficial as it allowed us to have discussions on our suggested competences, capturing and communicating the essence of a system. However, these guided discussions were lacking during the course and mainly surfaced at the "wrong" time, at the assessment.

Reflecting on student feedback, without focusing too deeply on a single piece of feedback, it seems critical to continue reflecting on the offered statements. The initial reaction to the student feedback of "a lot of work for information that was already known" might be that if it was already known, why is then a lot of work? This can mean several things that require more research. It might mean that students did not yet know everything, and at least did not know which parts of the information that they knew was relevant enough for the A3AO. It might also mean that our engineering students struggle with the visual style of the A3AO. Or it might just mean that benefits of creating an A3AO are missing or not made visible well enough.

6. Future Work

In the coming years, the authors will continue to develop the educational programs that they are involved in. Our aim is to continue to work with visual approaches that support an initial transition of mono-disciplinary engineers to systems engineers. Most importantly, we aim to educate a wide variety of bachelor and master students in systems thinking, a crucial 21st century skill.

In this context, we will continue to explore the usage of A3AOs. Based on our learnings in the case study presented in section 4, we aim to introduce the concept of A3AOs right at the start of the program instead of halfway through in the next educational year. Furthermore, we will only require a single A3AOs to be used (though more are allowed, for instance for certain aspects or subsystems), to support a more active and focused use of the tool in the development process of the case the students are working on. In that sense, we aim to address some of the concerns raised by the students by presenting the A3AO as a tool that supports along the way instead of being an end-of-the-line reporting tool. An interesting avenue is to focus on assessing the use and evolution of the A3AO and request a submission of the different versions in a portfolio, instead of only the final version.

In the continuation of research on the use of A3AOs in education, we suggest exploring and consolidating a typology for the use of A3AOs. Is it possible to formulate guidelines to utilizes A3AOs in different contexts? Is it possible to give practical implementation examples? Example questions that should guide potentials users to a supportive description could be the following. Are you supporting a development project? In which phase? Are you supporting a formal decision process? Are you starting a discussion? Are you informing an audience? Do you want to co-design a solution? Do you want to validate your solution? Do you want to trigger stakeholders for input? Do you want to educate stakeholders/employees?

The outcomes of the case study show that A3AOs have a potential role in kick-starting systems engineering and architecting competencies. The questions posed above show that there is still work required to get a better understanding of when, where, and how A3AOs are most relevant.

7. Acknowledgements

We would like to thank the students in the Master Next Level Engineering at the HU University of Applied Sciences Utrecht for their active participation in the educational program and their consent to publish and report on the results of their work. We would also like to extend our gratitude to the organizing committee of the SySTEAM inaugural conference as well as the reviewers.

Bibliography

Bonnema, G.M., I.F. Lutters-Weustink, and F.J.A.M. van Houten. 2005. “Introducing Systems Engineering to Industrial Design Engineering Students with Hands-On Experience.” In *18th International Conference on Systems Engineering (ICSEng’05)*, IEEE, 408–13. http://ieeexplore.ieee.org/document/1562885/.

Bonnema, G.M., I.F. Lutters-Weustink, and J Jauregui-Becker. 2016. “A Decade of Teaching Systems Engineering to Bachelor Students.” In *2016 11th System of Systems Engineering Conference (SoSE)*, IEEE, 1–6. https://ieeexplore.ieee.org/document/7542910.

Bonnema, G.M., K.T. Veenvliet, and J.F. Broenink. 2016. *Systems Design and Engineering: Facilitating Multidisciplinary Development Projects*. Boca Raton, FL, USA: CRC Press.

Borches, P.D. 2010. PhD Department of Engineering Technology “A3 Architecture Overviews.” University of Twente.

Brussel, F., and G.M. Bonnema. 2015. “Interactive A3 Architecture Overviews: Intuitive Functionalities for Effective Communication.” In *2015 Conference on Systems Engineering Research (CSER)*, Hoboken, NY, USA, 204–13. http://www.sciencedirect.com/science/article/pii/S1877050915002823.

Haveman, S.P., and G.M. Bonnema. 2016. “Communicating Behavior of Systems with the COMBOS-Method.” *Advanced Engineering Informatics* 30(4): 703–12.

https://www.sciencedirect.com/science/article/pii/S1474034616303214?via%3Dihub (June 1, 2018).

Hooft, D. ’t, J. Kroon, D. Omme, and G.M. Bonnema. 2020. “Enabling Systems Engineering in a New Product Development Process via a Tailored A3 Architecture Overview Approach.” *INCOSE International Symposium* 30(1): 168–82. https://onlinelibrary.wiley.com/doi/10.1002/j.2334-5837.2020.00715.x.

ISO/IEC/IEEE. 2011. “ISO/IEC/IEEE 42010 - Systems and Software Engineering: Architecture Description .”

Kooistra, R.L., G.M. Bonnema, and J. Skowronek. 2012. “A3 Architecture Overviews for Systems-of-Systems.” In *Proceedings Complex Systems Design & Management 2012*, ed. A. Rouzy M. Aiguier, Y. Caseau, D. Krob. Paris, 1–12.

Maier, M W, and E Rechtin. 2009. *The Art of Systems Architecting*. 3rd ed. Boca Raton, FL, USA: CRC Press.

Muller, G., and G. M. Bonnema. 2013. “Teaching Systems Engineering to Undergraduates; Experiences and Considerations.” *INCOSE International Symposium* 23(1): 98–111. https://onlinelibrary.wiley.com/doi/10.1002/j.2334-5837.2013.tb03006.x.

Muller, G. 2011. *Architectural Reasoning Explained*. Eindhoven: Embedded Systems Institute. http://www.gaudisite.nl/info/ArchitecturalReasoning.info.html.

SEBOK. 2023a. “SEBOK - A Brief History on Systems Engineering.” https://sebokwiki.org/wiki/Brief_History_of_Systems_Engineering (July 7, 2023).

———. 2023b. “SEBOK - System-of-Interest (Glossary).” https://sebokwiki.org/wiki/System-of-Interest_(glossary) (July 6, 2023).

———. 2023c. “SEBOK - System Architecture.” https://sebokwiki.org/wiki/System_Architecture (July 6, 2023).

Singh, V, and G Muller. 2013. “Knowledge Capture, Cross Boundary Communication and Early Validation with Dynamic A3 Architectures.” *INCOSE International Symposium (IS 2013)* 1(Figure 1): 420–32. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84896086800&partnerID=40&md5=c8223f5b975afaa05d1c2ade8f00d089.

Wiulsrød, B., G. Muller, and M. Pennotti. 2011. “Architecting Diesel Engine Control System Using A3 Architecture Overview.” *INCOSE 2012*.

Appendix I – “SE Posters” Description

- **Format**
    - Group composition: The assessment is executed in the same group as the Interdisciplinary Project Group
    - Deliverable: 3 posters in A3 Architecture Overview style
- **Guidance**
    - Create three posters, which together give a good overview of your Interdisciplinary Project, with the following scope:
        - **Poster 1 – Concept Definition**
            - Explain the problem scope and chosen concept – avoid detailing the solution. Include at least a functional, quantified and contextual view. Select other views as deemed applicable.
            - Additionally, the poster should support the project team to defend a trade-off that was made in the concept definition stage with relevant stakeholders
        - **Poster 2 – System Definition**
            - Explain the defined system solution from at least a functional, physical and quantification view. Select other views as deemed applicable
            - Additionally, the poster should support a discussion on a specific trade-off in the system, so that you can discuss this trade-off with relevant stakeholders
        - **Poster 3 – System Realization**
            - Explain the planned realization of your system in your project from at least a functional, physical and quantification view. Select other views as deemed applicable. Focus on the realization system (prototype), which might be different than the envisioned solution in the System Definition stage
            - Additionally, the poster should support a discussion on a trade-off, for example the relevancy and scope, of the envisioned realization
    - Include a title and short introduction that explains the scope and purpose of the poster. It is NOT required to deliver the “text side”, only the “model side” is required, but the scope needs to be clear!
    - The posters should support design discussions with a client and other potential stakeholders. Therefore, there should be a focus, especially with the use of visual aids on a specific trade-off in the system, and not necessarily on explaining everything that you did in that specific development stage (concept definition / system definition / system realization)

    - You are not limited to use only one model or diagram per type of view
    - Aim to provide a coherent visual design style and utilize storytelling – link different views where possible so there is not a sense of "we copy-pasted 4 diagrams and a few pictures on an A3"
    - Stick to the A3 paper format and make sure all text is readable when having the poster on a table in front of you
        - You thus have to be selective in which information you visualize!
    - Use references where applicable, you can make a separate box for those
- **Assessment Format**
    - Submit a PDF version of the posters on Canvas on the provided Assessment page. Clearly indicate group members and the theme of the posters in the filename. As filename, use the format "GroupX_Concept Definition.pdf", etc, where X is your group number or name.

The submitted posters are graded according to the provided rubric after a group project exam. Bring a print out of the posters to the project exam

Appendix II – "SE Posters" Assessment Rubric

The following table gives an overview of the assessment rubric for the SE posters assignment. The learning outcomes listed are sub-indicators of the overall learning outcome related to this assessment. Specifically, 1a concerns the systems definition poster, 1b the system definition poster, 1c the system realization poster and 1d addresses the overall capabilities of the students to discuss the system as a whole during the assessment.

Related Learning Outcome	Indicator	2	4	6	8	10
1a	The student has delivered a visualization of the concept definition which is about defining the problem, avoids the solution and supports a specific discussion topic in the problem domain.		Unclear goal and/or scope choices	Sufficiently clear goal but weak link to scope choices	Clear goal and strong link to scope choices	Clear goal and thought-provoking scope choices
1a	The student has delivered individual diagrams as part of the overall visualization that are internally consistent and include at least a context, functional and requirements view		Inconsistent diagrams, requested views omitted. Not useful for design discussions.	Requested views present but diagrams barely sufficient in quality. Information for design discussion lacking.	Requested views present including useful additions with consistent content. Serves properly for a design discussion.	Views and diagrams are consistent and innovative. Poster perfectly serves and directs design discussions.
1b	The student has delivered a visualization of the system definition which is about the design of a final envisioned system and supports a specific discussion goal in the solution domain.		Unclear goal and/or scope choices	Sufficiently clear goal but weak link to scope choices	Clear goal and strong link to scope choices	Clear goal and thought-provoking scope choices
1b	The student has delivered individual diagrams as part of the overall visualization that are internally consistent and include at least a functional, physical and quantification view		Inconsistent diagrams, requested views omitted. Not useful for design discussions.	Requested views present but diagrams barely sufficient in quality. Information for design discussion lacking.	Requested views present including useful additions with consistent content. Serves properly for a design discussion.	Views and diagrams are consistent and innovative. Poster perfectly serves and directs design discussions.
1c	The student has delivered a visualization of the system realization which is about the design of a fit-for-purpose realization system and supports a specific discussion goal in the realization domain.		Unclear goal and/or scope choices	Sufficiently clear goal but weak link to scope choices	Clear goal and strong link to scope choices	Clear goal and thought-provoking scope choices

1c	The student has delivered individual diagrams as part of the overall visualization that are internally consistent and include at least a functional, physical and quantification view		Inconsistent diagrams, requested views omitted. Not useful for design discussions.	Requested views present but diagrams barely sufficient in quality. Information for design discussion lacking.	Requested views present including useful additions with consistent content. Serves properly for a design discussion.	Views and diagrams are consistent and innovative. Poster perfectly serves and directs design discussions.
1d	The student is able to explain the relations between the problem, solution and realization poster and the relations between the three topics in the project		Not able to explain connection between posters, no understanding beyond posters	Able to explain connection between posters, limited understanding beyond posters	Provides value adding connection between posters, good understanding beyond posters	Innovative connection between posters, expert understanding beyond posters
1d	The overall delivery has a cohesive and consistent visual design that supports stakeholders in their understanding of the presented information		No cohesion between different posters visually and storytelling wise. Hard to gain understanding of system based on posters	Limited cohesion between different posters visually and storytelling wise. Possible to gain understanding of system based on posters	Good cohesion between different posters visually and storytelling wise. Easy to gain understanding of system based on posters	Excellent cohesion between different posters visually and storytelling wise. Posters together allow stakeholders to truly envision the key characteristics of the systems

Appendix III – “SE Posters” Assessment Examiner Questions

The following questions where prepared as (optional) prompts for the examiners to discuss the posters (or A3AOs) with the students in the oral assessment.

1. Could you select a stakeholder and describe how this stakeholder may interpret your poster(s)?

2. What kind of information would you like to collect through a specific discussion based on this poster?

3. In what kind of setting can these posters help to achieve what kind of goal?

4. Will you use these posters in your project with your client and stakeholders? If so, why? If not, why not?

5. How did your project characteristics influence the design of these A3AOs?

6. What does a SWOT for the A3AO as a tool look like? Particularly what threats do you see and what are remedies?

7. Did you apply systems thinking in the making of your A3AOs? If so, which and why? If not, why not?

8. ‘The knife cuts both ways’… Making an A3AO is valuable but using an A3AO for a discussion also is. Could you compare these two uses of this Systems Engineering tool? Could you make a distinction between the three SE-domains?

9. How does the A3AO compare to alternative ways of overseeing and communicating your system-in-the-making?

10. How do the relations between the poster illustrate the systems engineering process for your particular project?

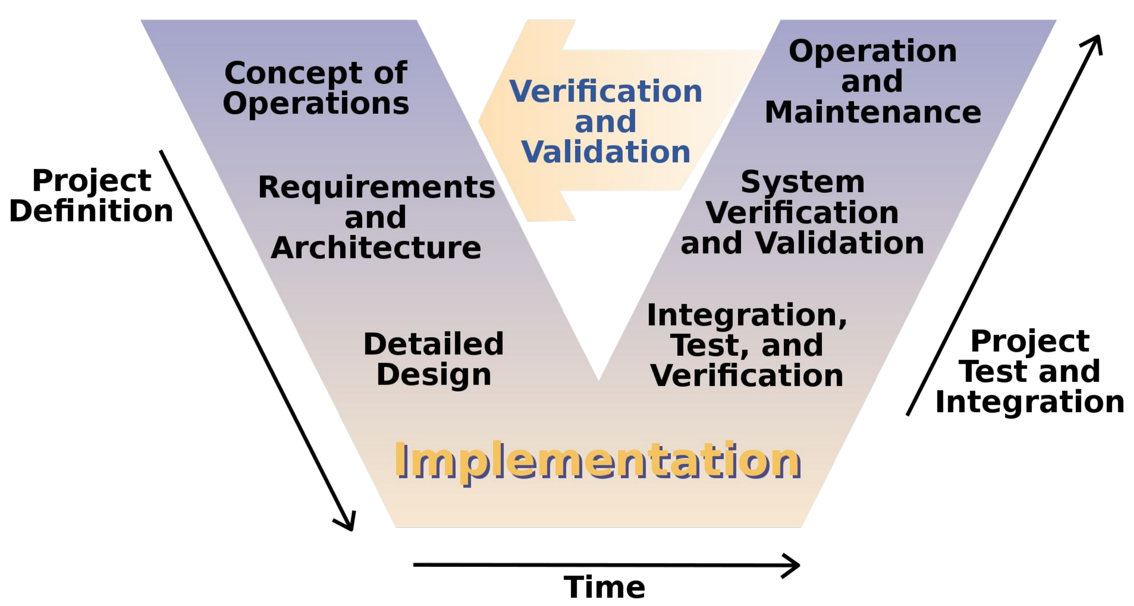
Lil Sys - A gamified mobile application aimed at promoting systems engineering to aspiring students.

G2 OPS | A leading provider of Systems Engineering Solutions | Matthew Frisbee | matthew.frisbee@g2-ops.com

Guiding Students through Systems Engineering

Lil Sys presents a unique approach that guides students through the stages of a typical system life cycle, using an exciting product design, such as creating a sports car.

Beginning with the Concept of Operations (CONOPS), students progress through system requirements, architectural design, verification and validation, testing, and finally, operation and maintenance.

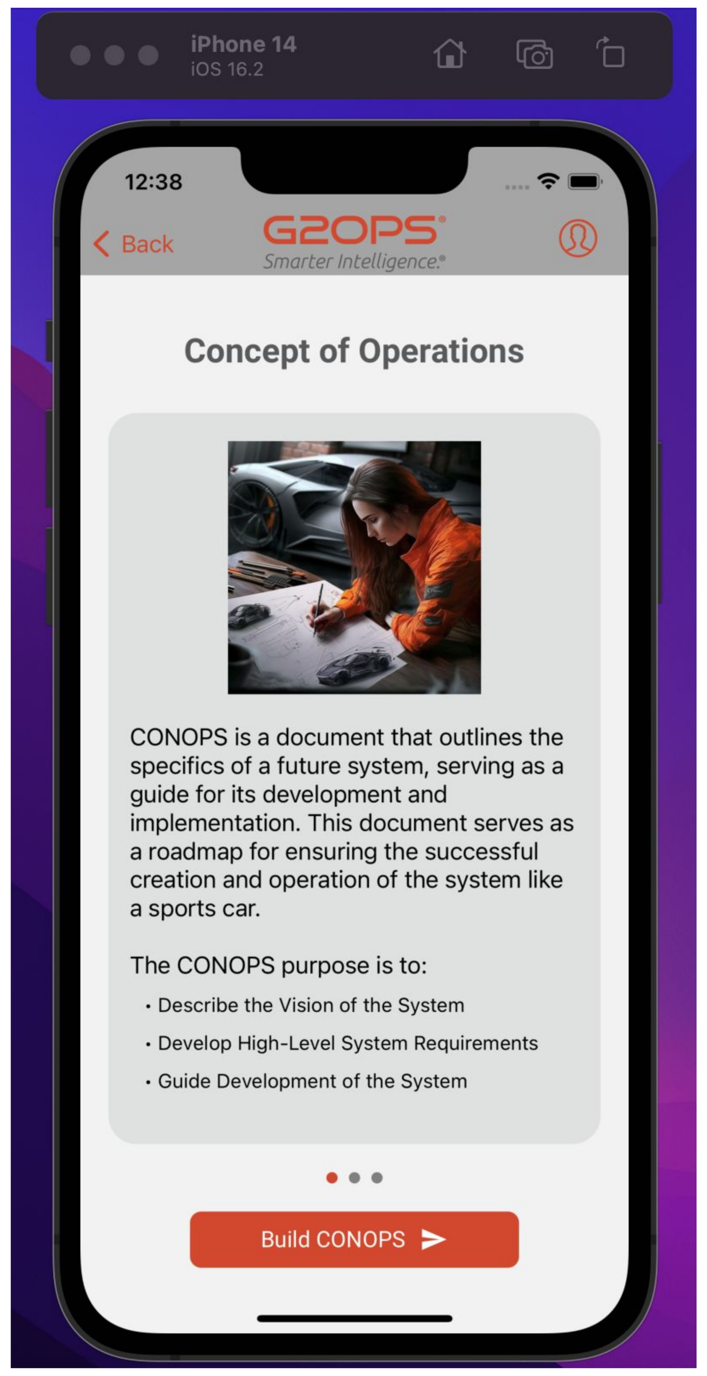


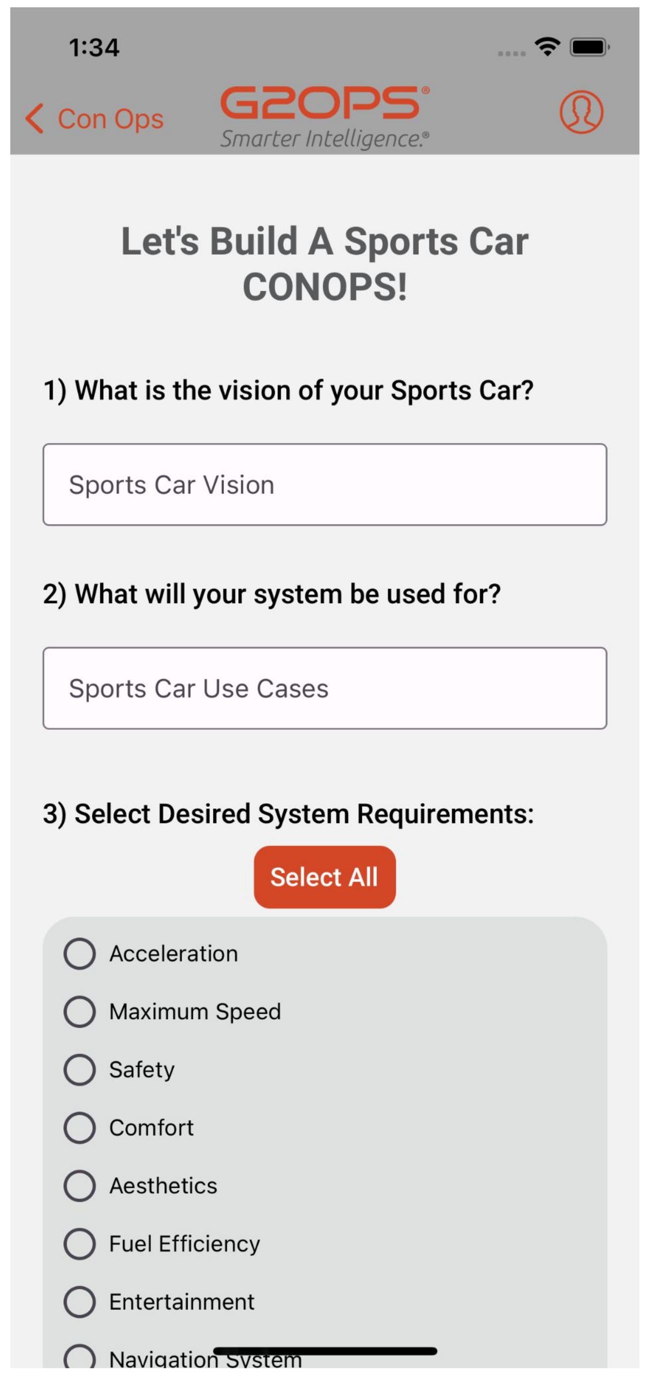
The Systems Engineering V-model. [1]

Concept of Operations

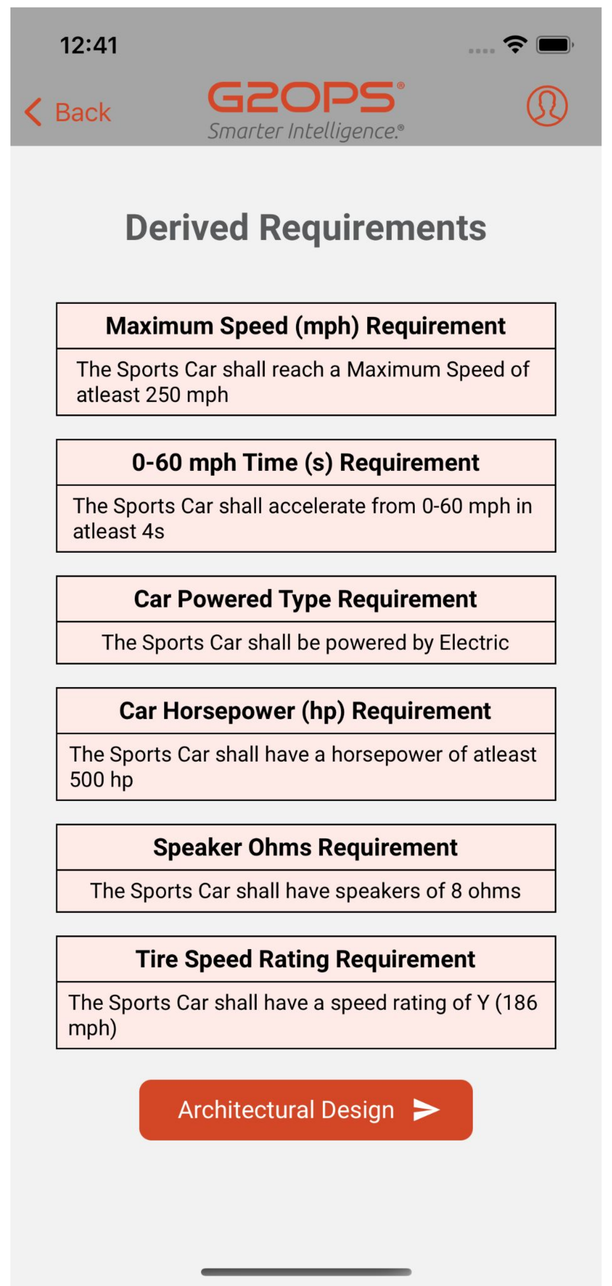
Lil Sys users will first navigate through a login or continue as guest page, where they then select to build their dream sports car.

Then, users will learn about the first step of the engineering process, Concept of Operations. Through these series of pages, users build their own CONOPS.





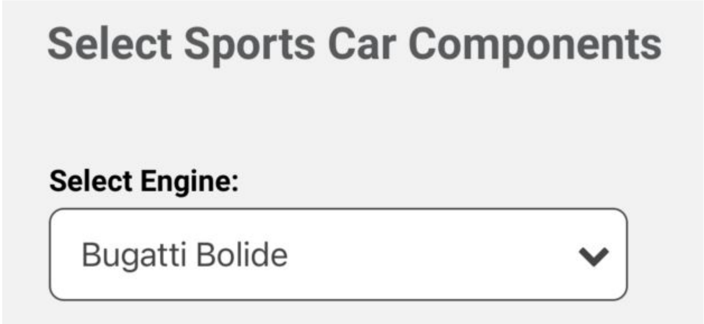
System Requirements & Architectural Design



After users complete the Concept of Operations, they will complete a form where they select specific parameters such as maximum speed.

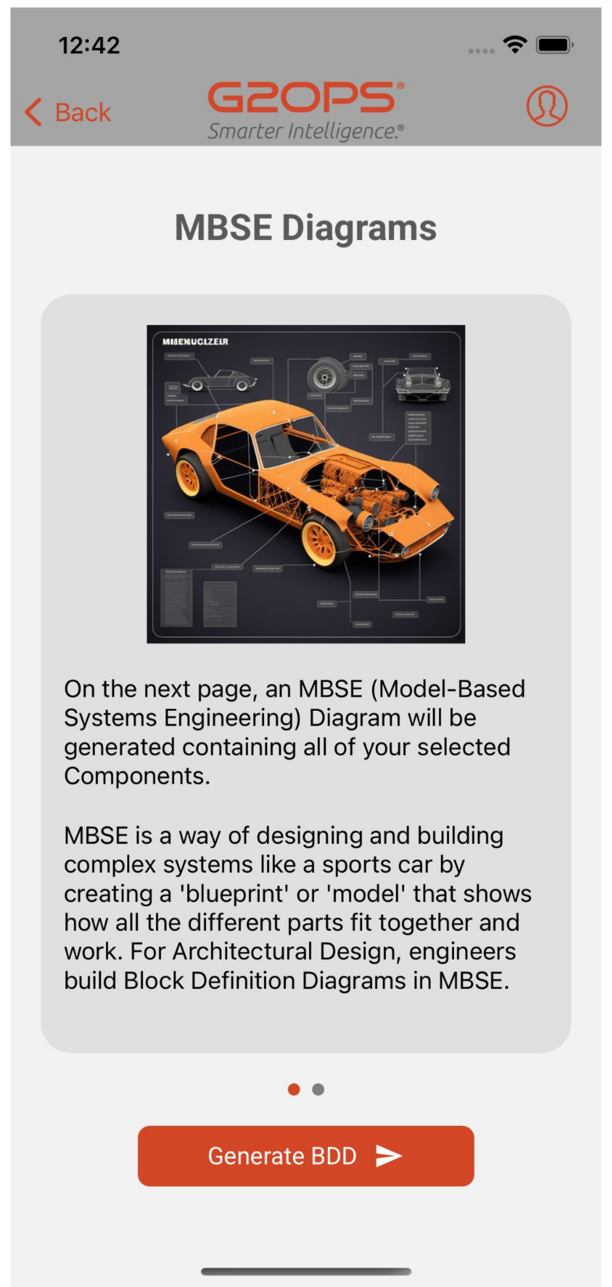
Requirements are then derived from the selected parameters and displayed on the next page as shown in the figure on the left.

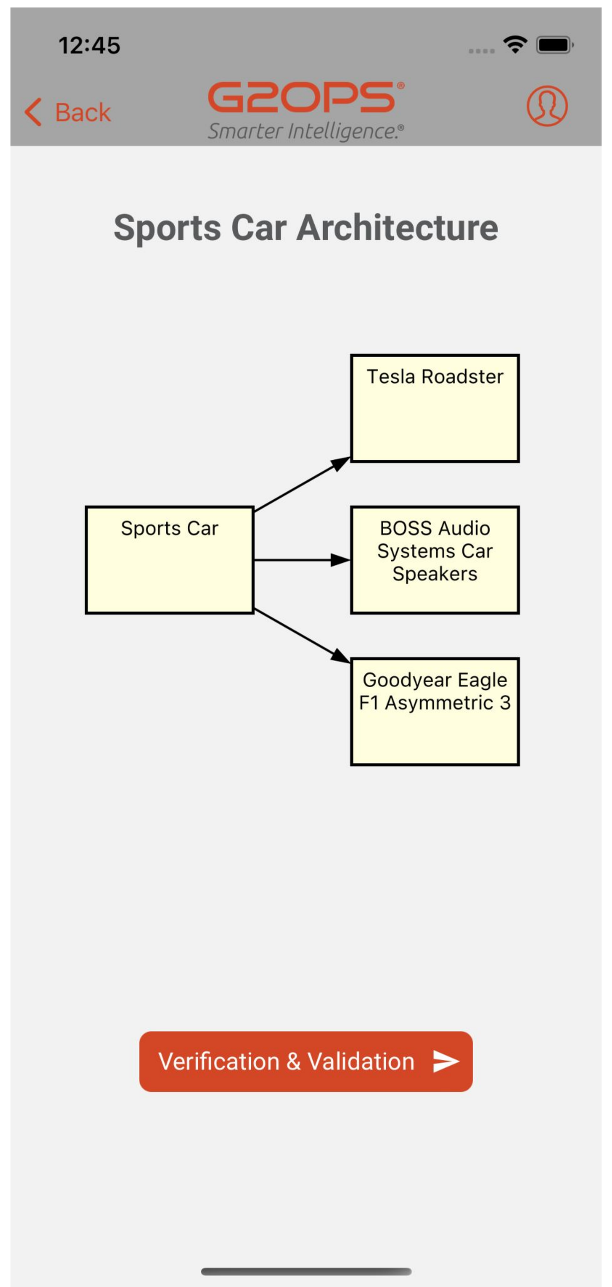
After generating their requirements, users will select car components that meet all of their parameters. The component selection also provides a feedback loop to the users. If the users selected a parameter configuration that does not exist in the real world, the app will provide a learning feedback loop for them to adjust their parameters.



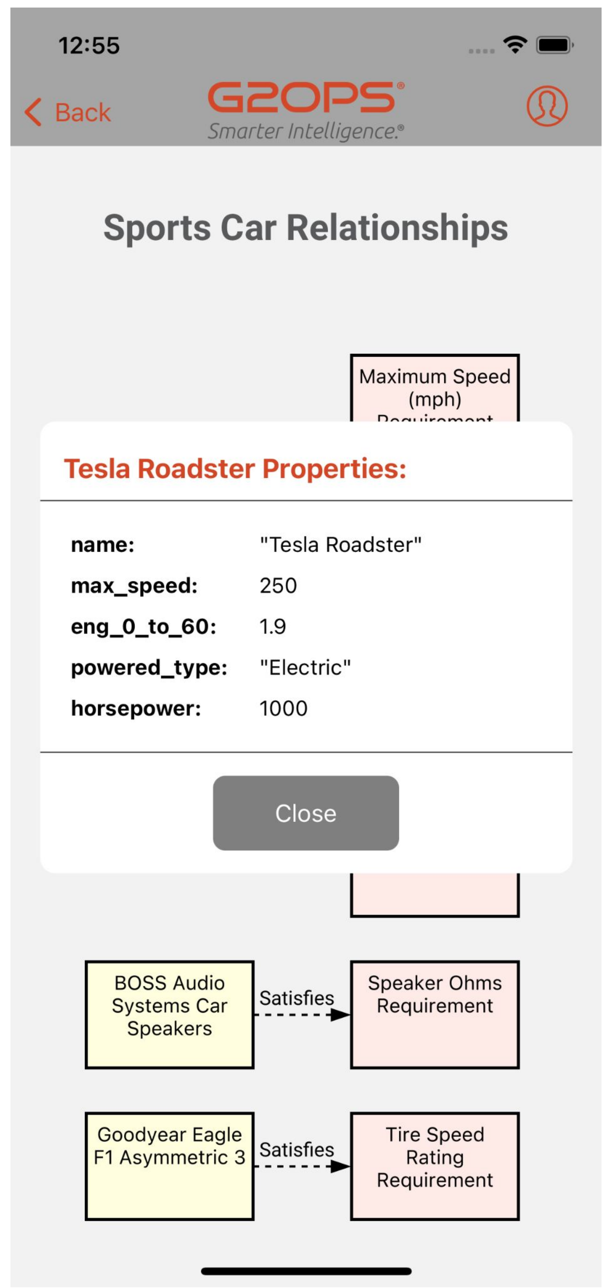
MBSE & SysML Diagrams

Once the users select their components, they now get to interact with MBSE & SysML Diagrams! The diagrams are fully interactive and the elements can be dragged around the screen. The first diagram is a Block Definition Diagram (BDD), where users interact with all of the components they selected for their sports car!





Verification/Validation & Testing



Next, users interact with a Requirements Diagram that displays how their architecture relates to their requirements.

The elements can be double tapped to view a specification window containing all of their relevant information.

The users learn how they can verify their system by ensuring all of their requirements are satisfied by an architectural component(s).

The users are now ready to enter the testing process. In the next beta release, users will be able to test out their sports car in a racing/obstacle game. The user's parameters and selected components will all have an impact on their sports car's performance in the game.

Additional Information & Upcoming Development

Lil Sys is a react native application that was developed using a variety of AI tools, from ChatGPT to Midjourney. The majority of the text, images, database, and react components were developed using AI tools.

In future releases, our goal is to also help students learn about the power of AI. As AI continues to progress in the next years, we hope to expand Lil Sys to allow users to select whatever system they want to develop, from a rocket ship to a submarine. The AI Tools would then generate the parameters, contextual information, and images from their selected system type.

In the near future, our primary goal is to move Lil Sys from its current alpha release to a beta release. Lil Sys will be ready for beta release after:

1) Finishing internal alpha testing
2) Implementing the game into the Lil Sys application
3) Adding more requirements and components to enhance the user experience

Lil Sys is currently in the alpha stage for internal testing on both the Apple App Store and Google Play Store. If you would like to become a tester for our upcoming external test release, please provide your device type (Android/Apple) and your email to g2ops.sw.srvcs@gmail.com.

References

1. *Clarus Concept of Operations* Archived 2009-07-05 at the Wayback Machine, Publication No. FHWA-JPO-05-072, Federal Highway Administration (FHWA), 2005.

Bringing Back Humanity in a Tech-Driven World: (Re)Incorporating the Arts into Engineering Curricula to Make STEAM Reality and Enhance Disciplinary Convergence

Rock Mendenhall
Colorado State University
Fort Collins, CO
rock.mendenhall@colostate.edu

Dr. Steven Simske
Colorado State University
Fort Collins, CO
steve.simske@colostate.edu

Dr. Pamela Vaughan Knaus
Colorado State University
Fort Collins, CO
pam.vaughan_knaus@colostate.edu

Copyright © 2023 by Rock Mendenhall. Permission granted to INCOSE to publish and use.

Abstract. The accelerated integration of technology into our everyday lives has shifted, in many cases intentionally, to proposing technology as an end in itself. The loss of emphasis on the arts – including history, cognitive science, and philosophy – is often a consequence of the emphasis on the STEM (science, technology, engineering, mathematics) aspects of solutions. Example technical solutions include computers, artificial intelligence (AI), and digital engineering. In this paper, the authors present methods to fuse STEM (in particular, engineering) and the arts, creating STEAM approaches to significant societal systems via more broadly interdisciplinarian research methodologies. The main methodology introduced is Cognitive, Historical Augmented Intelligence Systems Engineering (CHAISE). The CHAISE approach is intended to provide a platform for the convergence of the arts and engineering by innovating curricula changes to transform current STEM programs into STEAM curricula, and to create an advanced systems engineering framework that merges several disciplines, including the arts. The current popularity of AI and large language models (LLMs) requires the art pillars of history and philosophy to ensure that the output created by these increasingly automated systems is relevant to humans. CHAISE-supported approaches to achieve these goals will be described in the paper. One CHAISE approach is to provide a panel of AI experts, rather than a single AI technology, in many applications to provide improved consensus, reduced severity of errors, and overall improved system resilience. A second CHAISE approach is to rapidly mine past engineering historical feats to formulate case studies that improve design by telling effective stories, patterns, and lessons learned. Additionally, this paper includes authors that provide insight as PhD professors (1x Systems Engineering, 1x History Honors). The proposed material investigates how to converge the arts, engineering, and systems thinking by innovating curricula changes and transforming current STEM programs into STEAM curricula. The STEM and arts programs at universities need to evolve to ensure accuracy and "diversity of mind" in a tech-driven environment.

A Platform for Convergence of the Arts and Engineering

The Cognitive, Historical Augmented Intelligence Systems Engineering (CHAISE) framework is a platform to help merge the arts with engineering technology, like Artificial Intelligence. Engineering frequently focuses on solving problems while the arts focus on “what could be” or is possible if we dream it. One could argue that both fields perform the tasks of solving challenges and imagining, but if we take the optimal areas of the arts and merge them with optimal engineering techniques, SySTEAM versus STEM is a more powerful solution. The Systems Engineering (SE) discipline must change its traditional SE mental model to grasp the new paradigm of CHAISE to deal with our current reality; otherwise, SE principles will no longer be fast enough to keep up with technology trends. Humans and technology must work together to achieve success, instead of going at it alone with one or the other. CHAISE accounts for the convergence of the arts and engineering into an integrated SySTEAM model, versus solely concentrating on engineering.

In this paper, the authors introduce the CHAISE framework as a metacognitive platform to pave the way for current and future SE approaches. The ability to quickly evaluate, correlate, and create value from vast amounts of cross-disciplinary data, across the arts and engineering, will be paramount for the future of systems engineering. Albert Einstein quoted, “Knowledge is experience, everything else is just information.” Henry Bloom said, “Information is endlessly available to us-where shall wisdom be found?” The synthesis of various ideas into a holistic SySTEAM framework will benefit engineers abroad by systematically integrating technology with the arts to realize designs that reflect ethical humans. The Massive Transformative Purpose (MTP) of CHAISE is cognitively connecting limitless data and historical experience to the human mind, to perform engineering better and faster!

The CHAISE framework involves the integration of meta-algorithmics and meta-analytics. Meta-algorithmics and meta-analytics combine multiple algorithms to attain better overall system behavior and minimize the severity of errors. Machine intelligence and human intelligence complement one another, especially if we design solutions with this consideration. A focus on the convergence of the human mind and machine, sometimes known as the ‘cognitive digital twin’ is essential in AI design and solutions. CHAISE emphasizes using multiple AI models trained differently, analogous to distributed cognition across human teams and/or panels. CHAISE capitalizes on a collective structure with multiple disciplines and intelligences working together to help realize metacognition experienced on the human level.

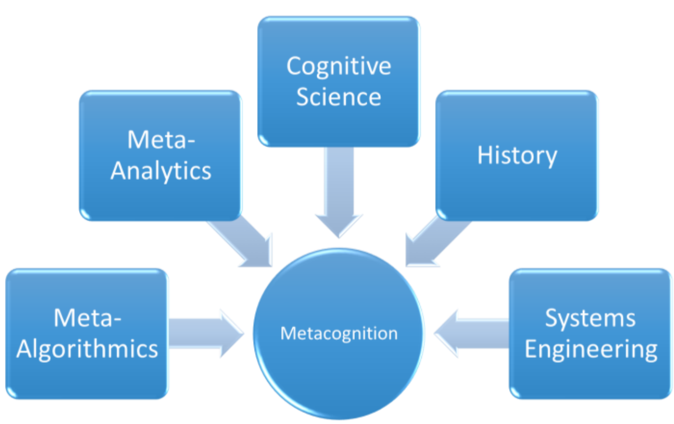


Figure 1. Cognitive, Historical Augmented Intelligence Systems Engineering Foundations

It is difficult to be a great leader, let alone a good engineer without knowing and learning from history. “Chronicles in the ancient world tell us about failures, conquests, and so on, but they do not talk about meaning. History attributes meaning to those events. By 2014, the National Assessment of Educational Progress showed that only 18% of middle schoolers could be proficient in American History” (Guelzo). Since 2011, the number of history majors at American universities has declined by a staggering 33% (Pettit). Due to a limited number of jobs available for historians, students are choosing to enroll in other degrees, to include STEM. Also, hyper-politicization has made more people negatively perceive history. History exists to give one prudence, caution, elevation, regret, or inspiration.

William Faulkner quoted, “the past is not dead; in fact, it’s not even past.” Nathan W. Dougherty, American civil engineer cited, “The ideal engineer is a composite … He is not a scientist, he is not a mathematician, he is not a sociologist or a writer; but he may use the knowledge and techniques of any or all these disciplines in solving engineering problems.” James Kip Finch quoted, “The engineer has been, and is, a maker of history.” Historian Patrick Allitt quotes, “Without History, we are blind and in the dark.” “History teaches you about the future, identity, and what is important. Not asking why will doom you to complacency and inaction” (Burt). Knowing the past shapes, the present and the future. Leonardo da Vinci quoted, “The greatest deception men suffer is from their own opinions.” Da Vinci also quoted, “Learning never exhausts the mind.” It is extremely important to learn from history, and not to forget the insight history provides, and reduce the comfort to only live in the present.

In modern technology, ethics plays an essential role. During a recent Ted Talk, Olivia Gambelin discussed the following. “In this life, our purpose is based around the values that define us. We seem to have forgotten to align the purpose of our technology and systems with the values we have as humans. Our technology reflects our humanity, and it is time for that technology to reflect what it means to be human” (Gambelin). In both digital technology and AI, it is essential to revisit historical lessons and to include ethics and logic, dating back to the ancient Greeks.

While it is important to perform introspection, it is just as important to value "extrospection." Extrospection is the observation of things external to one's own mind. Introspection can be quite risky for an engineer conducting a design, while extrospection enables the engineer to focus on the events and other disciplines in the environment unfolding around them. Extrospection is also critical in understanding and empathizing with historical context. In summary, extrospection prevents tunnel vision and allows one to zoom out and understand events and perspectives around them.

Modern science is deconstructing the mind and multiple disciplines are using their own terminology and methods to study the mind. Each discipline tends to have its own conceptual vocabulary and mental model. The disciplines include neuroscience, computer science, artificial intelligence, linguistics, anthropology, and psychology. In a Ted Talk at the University of Toronto, Dr. John Vervaeke highlighted that a core challenge exists, in that all the previously mentioned disciplines describe the mind and cognition in different terminology. “The behavioral level, cultural level, and language level within the brain are not working in isolation. They are casually interacting with one another through these various levels” (Vervaeke). Therefore, the use and importance of cognitive science is vital in serving as a bridge. “Cognitive science takes all the empirical information, disciplinary theory, and tackles the daunting task of bridging and integrating conceptual vocabulary, so that these various disciplines can talk to each other in a mutually informative and transformative way” (Vervaeke). This is why we emphasize that the future of systems engineering must integrate cognitive science via frameworks, like CHAISE. "If the multiple disciplines can integrate, then we can capture the way the levels of the mind are integrated and avoid equivocation and its corresponding confusion. As cognitive science reintegrates the mind, it is putting into human hands the potential to put the mind back together again in alignment with the world" (Vervaeke). From this, SySTEAM combines several disciplines, but without a "cognitive" approach or the integration of cognitive science, then it will be hard to create a common vocabulary to unify and talk across the disciplines involved. SySTEAM also provides the potential to reintegrate the arts, STEM, and an array of disciplines, into a unified framework, to enable metacognition.

Currently, INCOSE has two main initiatives regarding artificial intelligence and systems engineering. Systems Engineering for Artificial Intelligence (SE4AI) applies SE methods to learning based systems' design and operation. Key research application areas within SE4AI include developing principles for learning-based systems design, life cycle evolution models, & model curation methods. Artificial Intelligence for Systems Engineering (AI4SE) applies augmented intelligence & machine learning techniques to support SE practices. To meld Systems Engineering methods with Artificial Intelligence technologies, a focus on the cognitive sciences and arts is required, and seriously incorporating the pillars of SySTEAM aids this focus.

Transdisciplinary Convergence

In today's current landscape, accelerated by the recent inundation of possibilities based on generative Artificial Intelligence (AI), there is frequently the idea that technology alone will solve key problems. Digital technology has become a core of our modern society, but without a focus on how technology is employed via the arts and user experience, technical solutions while sound, can significantly fail if a holistic combination of the arts and engineering are not implemented.

Noted engineering professor Vivek Wadhwa quoted, "An engineering degree is very valuable," Wadhwa writes, "but the sense of empathy that comes from music, arts, literature, and psychology provides a big advantage in design. … A psychologist is more likely to know how to motivate people and to understand what users want than is an engineer who has worked only in the technology trenches" (American University). Ali P. Gordon, Ph.D., an associate professor in mechanical and aerospace engineering at the University of Central Florida. "Programmers and engineers are increasingly teamed up with artists to co-develop software, products, renderings and more" (UCF). AI, even generative AI (GAI) alone cannot accurately represent several aspects and talents of human behavior.

"Interdisciplinary collaboration is the new normal," says Gordon. "Many of the world's top engineers and scientists have an appreciation for the arts or are artists themselves. Their interests and talents cannot be contained in a sole discipline" (UCF). Technology has aided in helping people realize how many things are interconnected and interdependent. Engineers can design technical solutions to solve challenges, but in a vast world of interdependencies, they rely on the perspectives from multiple disciplines to construct effective answers. Computers and even the AI buzz can aid in developing solutions. "However, there remain certain soft skills a computer simply cannot replicate in the workplace: teamwork, cooperation, creativity, and adaptation to change, to name a few" (UCF). As a result, there is still a demand for a 'human in or on the loop' due to their innate skills that machines cannot emulate.

The disciplines required to merge systems engineering, the arts, and STEM into a holistic SySTEAM foundation are highlighted in Figure 2.

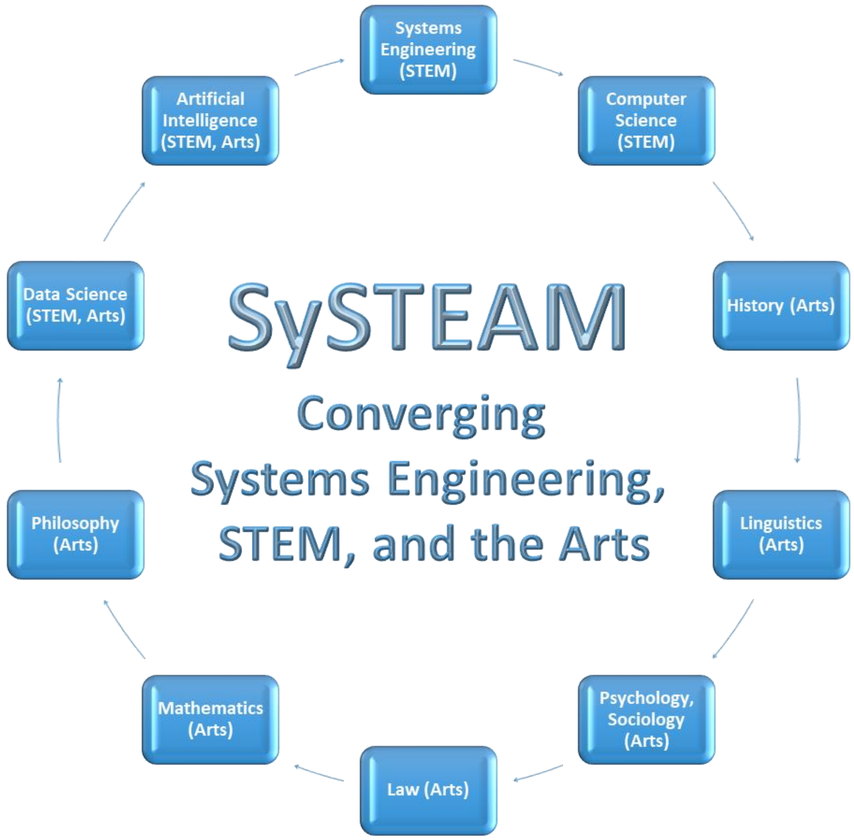


Figure 2. SySTEAM Interdisciplinary Convergence of Multiple Disciplines

Leonardo Da Vinci was known as the quintessential "Renaissance Man." Da Vinci was a gifted painter, architect, anatomist, engineer, musician, and inventor. Da Vinci epitomized the concept of systems thinking in the following quote, "Principles for the Development of a Complete Mind: Study the science of art. Study the art of science. Develop your senses – especially learn how to see. Realize that everything connects to everything else" (Quotefancy.com). People and articles have deemed Da Vinci as one of the greatest thinkers in history (Demange & Ember). Leonardo additionally quoted the following about actively using one's mental abilities: "Iron rusts from disuse, stagnant water loses its purity and in cold weather becomes frozen; even so does inaction sap the vigor of the mind" (Demange & Ember).

Da Vinci is the embodiment of interdisciplinary STEAM thinking. "Scientific American reported that interdisciplinary scientists are far more likely to become Nobel Laureates than their more focused counterparts. In fact, Laureate scientists are seventeen times likelier than the average scientist to be a painter, twelve times as likely to be a poet, and four times as likely to be a musician" (Payes). The arts stimulate cross-disciplinary thinking, which stimulates cross-disciplinary connections, which is the hallmark of invention.

"The Erie Canal was the first major infrastructure project in the history of America," says Derrick Pratt, museum educator at the Erie Canal Museum (Roos). The workers building the canal first broke ground on July 4, 1817. "The first challenge to building the Erie Canal was that the United States did not have a single college of engineering or any native-born engineers. So, the Canal Commissioners had no choice but to hire an amateur crew of self-taught local engineers that included a few inexperienced surveyors and at least one local math teacher. The two chief engineers were Benjamin Wright and James Geddes, lawyers by trade who learned how to survey by prosecuting land disputes" (Roos). As a result, the Erie Canal resulted in the creation of Rensselaer Polytechnic Institute in Troy, NY in 1824. RPI became the United States' first civil engineering school.

Benjamin Wright sent his assistant, Canvass White, to spend a year in England to learn everything he could about locks, the brilliant method first conceived by Leonardo Da Vinci for raising and lowering boats to accommodate changes in elevation" (Roos). "Leonardo da Vinci's Invention for the canal lock was one of his most enduring achievements. The lock he invented – the miter lock, is still in use today at almost any canal or waterway you visit in the world" (leonardodavincis-inventions.com). Canvass White ended up solving one of the main construction problems for the Erie Canal. At that time, the only hydraulic cement was formed in Europe and was extremely expensive to ship. Therefore, the American engineers needed to devise a better alternative. White and one of his coworkers, Andrew Barstow, identified a local source of limestone that could set and harden underwater. The Erie Canal, which is still used to this day, is an engineering marvel. Leonardo da Vinci's brilliant cross-disciplinary invention for the canal lock has endured across centuries and proves the value of STEAM.

Another visionary and cross-disciplinary thinker was John Fletcher Hanson. Mr. Hanson was a risk taker, a policy influencer, a strategist, and leader across a broad spectrum. Dr. James McWilliams in a book review quoted "Hanson was somewhat of a nineteenth century Renaissance man of the South whose interests spanned from journalism to industry to politics" (Dunn). Mr. Hanson owned nine mills, founded the Columbus Power Company to generate hydroelectric power, owned the "Macon Telegraph" newspaper, and served as chair of the Central of Georgia Railway and the Ocean Steamship Company. Following the American Civil War of 1861-1865, he realized that the South needed to transform its agricultural economy into an industrial economy. Hanson propelled legislation in 1882, resulting in the establishment of the Georgia Institute of Technology in 1885. "The Georgia Institute of Technology consistently ranks among the country's top 10 engineering institutions and has a reputation as a global leader and innovator. The College has eight engineering schools, each ranked at the top of their respective fields" (Georgia Tech). Hanson's ability to think across and own companies across several disciplines culminated in one of the world's top universities and an industrial, technology-driven South that is the opposite of the economy that it was 158 years ago. He challenged traditional mental models on labor, politics, education, and race issues, in the Macon Telegraph and his portfolio of companies. Hanson helped in not only revolutionizing the South, but in progressing the United States overall. His legacy lives on through the millions of cross-disciplinary students that have attended and graduated in across the arts, business, policy, history, economics, psychology, disciplinary engineering, and systems engineering from the Georgia Institute of Technology.

We think the convergence of systems engineering, the arts, and STEM into a holistic CHAISE framework and method of thinking across disciplines is central in formulating solutions for the 21st century and beyond. If technology, to include AI, is to reflect humanity, then the arts, humanities, ethics, and history are vital in ensuring solutions align to our human values. As Leonardo da

Vinci quoted, everything is connected, so we recommend against specializing in disciplines solely. An undergraduate professor once told me, you go to college to get a well-rounded education, otherwise, why not attend a trade school. SySTEAM is and will be a pivotal driver for future inventions that increase symbiosis between machine and human.

Adjusting the Educational Curriculum to Realize STEAM

STEAM as opposed to STEM is not a new concept. Frequently, students gifted in science and mathematics choose not to attend STEM-exclusive schools, prior to college, choosing instead to receive better-rounded training. Such students possess a passion for music, drama, rhetoric, and other forms or art, humanities, and social sciences. These students often choose schools that offer exposure to both the arts and science. If schools, including colleges, evolve to offer a SySTEAM curricula, they will attract higher rates of attendees and potentially increase "diversity of mind." The "diversity of mind" principle focuses on enhanced mental models by combining perspectives, innovations, and ideas across multiple disciplines-domains. In psychology this would be recognized as distributed cognition. The authors think a "hands-on" approach to teaching engineering solutions and application of critical thinking, versus brute force memorization of subject matter, would be one way to think about bringing SySTEAM to life. Two of this paper's authors, who are professors at the masters and PhD levels, have numerous ideas of potential ways to realize SySTEAM at the university setting.

At the collegiate level, we propose adding an "incentives" structure for Department Chairs and Academic Deans to better incentivize professors to create a higher number of interdisciplinary classes. If a STEM professor coordinates with a liberal arts professor on a subject such as data science, students can obtain a diverse perspective on both the user experience and mathematics portions of a popular subject encompassing STEAM. Both engineering and arts professors can collectively form the course material and co-teach lectures to enable "diversity of mind" and encourage students to learn material they would not take alone in an arts-focused or STEM-focused curricula. This combined STEAM curricula promotes cross-disciplinary discussion and feedback across a wide spectrum of students that normally would not take place. It also enables holistic teams of arts and engineering students to collaborate on course projects to improve solutions through consideration of both degree tracks.

Competitive universities attract high-achieving and multi-cultural students by offering an interdisciplinary elective which provides diversification through interdisciplinary STEAM tracks where a STEM student can minor in a liberal arts degree and vice versa. This reintroduction of the arts into engineering benefits the future workforce by delivering well-rounded employees, steeped in multiple disciplines, that exhibit "diversity of mind." Steve Jobs boldly announced that "part of what made the Macintosh great were the people working on it were musicians, poets, artists, zoologists, and historians who also happened to be the best computer scientists in the world" (Madni). An engineer or liberal arts graduate who experienced systematic STEAM thinking in their educational experience, will formulate innovative thoughts that result in impressive solutions. It is crucial that higher education venues enhance curricula in the 21st century to develop and mature STEAM-minded people who might transform the world through elegant design solutions.

Universities can offer interdisciplinary STEAM certifications to promote lifelong learning and growth opportunities to expand one's degree(s). Large Language Learning Models (LLMs) may provide an avenue to promote online certification courses that allow people to learn novel items across disciplines. Interest in multiple disciplines will vary at different seasons in one's life. Therefore, creative certification tracks which promote personal growth and creative thought throughout a lifetime, may end up being more relevant than a college degree. The ability to expose oneself beyond a degree prepares students for lifelong success—juxtaposed to a degree that is a snapshot in time--frequently during early exposure to education.

A case study surrounding STEM's dominance may be found among undergraduate honors students. Often, Honors Programs are "STEM-heavy" regarding enrollees' majors, minors, and professional goals. For example, at Colorado State University, a growing and disproportionate number of those in its University Honors Program represent the Colleges of Engineering and Business. Fewer and fewer have declared a major in Liberal Arts or Arts and Humanities. Due to the UHP's nature, its deliberately modestly enrolled seminars envelope students in interactive, sharing, and open learning communities. Increasingly, this is like-on-like, as the lion's share of participants tends to represent a limited focus because sciences and math dominate; seminar participants are only able to discuss that which they have been exposed to. Consequently, classroom conversations become restricted to those in which students are already immersed in their STEM classes, labs, and readings. The few Liberal Arts/Arts and Humanities UHP professors find their classes filling—and overfilling—quickly as many STEM students seek relief from their science-based regular circular. Students without access to an Honors Program may encounter even fewer arts and letters selections.

More options might include the following. If a STEM student majors in a STEM-centric class that lasts a semester, offer the opportunity to offer two seven-week liberal arts courses during the same semester to allow separation from mid-terms and final exams so students can focus on learning the arts without interrupting engineering exam study sprints. This would work in the same manner for liberal arts students who take STEM classes as an accelerated elective course of study. Additional paradigm shifts may include offering four 3-week summer courses in the inverse portion of STEAM (for example, an engineering major takes four arts and humanities courses). These summer classes could take place in a more engaging and relaxed learning environment where students focus on application, rather than memorization.

Offering master's degrees, baccalaureate degrees, or minors in engineering history fills a void of engineers living in present technology, and promotes studying past technologies that have purpose today, such as da Vinci's canal lock. "The history of engineering provides an invaluable collection of case studies for understanding better the nature of engineering itself and for providing invaluable models, lessons, and caveats for its practice. We gain perspective across fields of engineering by knowing their various and interrelated histories. A historical perspective assists engineers in identifying failure modes and catching errors in logic and design" (Petroski). Integrating engineering history into specialized engineering degrees at the baccalaureate level or including engineering history with specialized thesis topics (for example, automotive engineering history, aeronautical engineering history, space systems design history) at the master's level, matures teams with individuals who can draw parallels across disciplines and between past and present. This will enable product development and engineering teams to boost success rates, usability, and safety in designs.

Commuting accounts for an abundance of time for students. Employing 21st century mobile technologies, an emphasis could be placed on teacher-provided subjects in podcasts, video recordings, audiobooks, and/or eBooks to permit students to learn on the go. Today's students are accustomed to learning digitally, thus, offering courses in this manner, allows students to optimize time during the day they may otherwise squander on non-learning activities.

Appreciation for the arts, STEM, systems thinking, and enhancing one's mental models is an integration necessary for elementary through high school education. If a SySTEAM foundation is taught from the early onset of elementary school with a holistic course emphasis, then students will increase their "diversity of mind" and tie concepts from one discipline to the next, realizing da Vinci's remark that everything is connected. In the age of digital technologies and AI, critical thinking and the scientific method, prevent students from memorizing simply to pass tests and accepting digital artifacts and presented metanarratives at face value.

A SySTEAM foundation refocuses on learning material and applying it in the classroom. Figure 3 highlights the pillars of convergence to realize SySTEAM. Twenty years ago, students had to conduct research in a physical structure such as a library. This in-person, hard copy artifact approach taught one to examine multiple topics, read across all of them, interpret multiple perspectives, frame their own mental model through applied research, and formulate a decision-thesis. Algorithms and specific search engines today tend to filter out robust news sources and international analyses performed around the globe. If AI and GAI are trained on this same data, the data is inherently biased, and the generated research results will be skewed and inaccurate. Digital technology is powerful; it produces vast amounts of critical information, but without systems thinking and "diversity of mind" to review differing opinions results in students that blindly trust data results given to them from a search engine or GAI prompt. An analogy is, although modern aircraft have an autopilot system, pilots still learn to fly the plane manually and how all systems are interconnected, before learning the digital autopilot features. Educational curricula, similarly, must ensure manual basic processes are introduced before instilling a reliance on digital applications.

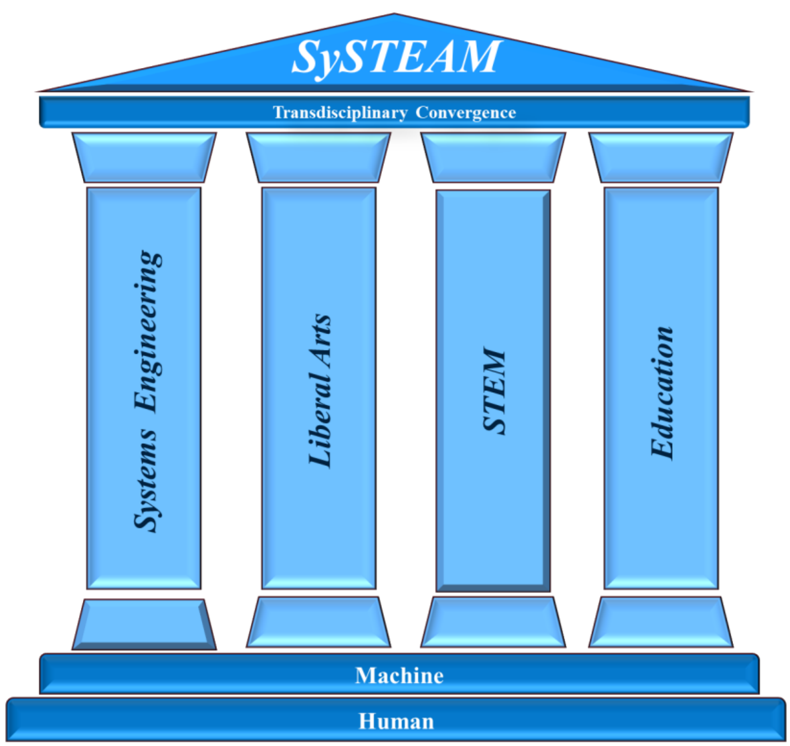


Figure 3. Pillars of Convergence for SySTEAM

We finish this section with a quote from Harvey S. Firestone--"The growth and development of people is the highest calling of leadership." When developing today's students, more dynamic frameworks encompassing the convergence of the multiple disciplines within the arts, STEM, and systems engineering must be developed and continuously improved in order successfully mold the employees and systems engineering leaders of the future.

Conclusion

In summary, the arts are not "added on" to the STEM curriculum as something different, something segregated, something "unusual," but are instead naturally incorporated, e.g., aesthetics when you consider different designs under the light of engineering specifications. For example, if you are employing additive manufacturing (3D printing) and the three pigments green, cyan, and blue reduce the mechanical strength of a part by 2%, 15%, and 7%, respectively, where 10% moves it below the safety factor, then green is preferred, blue is allowed, and cyan is not allowed. The artist then works within these constraints for her palette. A SySTEAM emphasis fosters an enhanced holistic and systematic approach for merging systems engineering, the arts, and STEM together in unison.

The SySTEAM methodology helps merge the past and present in order to create a more robust path forward incorporating the best of the arts, STEM, and systems engineering. While systems engineering harnesses relevant STEM processes and the integration of the engineering disciplines, it also focuses on the successful realization of a system. Therefore, systems engineering is correlative to the arts in using the "logic model" which initiates design with the end goal in mind (and not the existing technologies or skills in an organization). Like the arts, systems engineers tend to use this logic model approach to work backward (or "top down") from what the customer wants, specifying the technologies and processes only after deciding on the design, test plan, and operations. STEM folks or specialized-discipline engineers, on the other hand, tend to work forward (or "bottom up") from the tools, current technologies, and trade secrets they already know to get to the end products (designs, test plans, operations, etc.). Working both "top down" and "bottom up" together using the SySTEAM features, yields a much more robust, resilient, and improved design.

References

American University 2018, ‘STEM vs. STEAM: Why One Letter Matters’, Accessed at STEM vs. STEAM: Why One Letter Matters | American University

Burt, L 2021, ‘Study History to Connect to Ourselves and the World Around Us”, Accessed at Study history to connect to ourselves and the world around us. | Lydia Burt | TEDxYouth@Abbotsleigh - YouTube

da Vinci, L 2023, Principles for the Development of a Complete Mind, Accessed at https://quotefancy.com/quote/852625/Leonardo-da-Vinci-Principles-for-the-Development-of-a-Complete-Mind-Study-the-science-of

Demange, D, & Ember S 2011, ‘Leonardo da Vinci: One of the Greatest Thinkers in History’, VOA News, Accessed at Leonardo da Vinci: One of the Greatest Thinkers in History (voanews.com)

Dunn, L 2016, *Cracking the Solid South: The Life of John Fletcher Hanson, Father of Georgia Tech*, Mercer University Press, Macon, GA (US).

Gambelin, O 2022, ‘How Ethics will Change the Future of Technology’, Accessed at How ethics will change the future of technology | Olivia Gambelin | TEDxPatras – YouTube

Georgia Tech 2023, “College of Engineering: Facts and Rankings”, Accessed at Facts and Rankings | College of Engineering (gatech.edu)

Guelzo, A 2021, ‘The War on History-and Why It Matters: A Conversation with Allen C. Guelzo’, Accessed At https://youtu.be/EHXk0SKvAmE

Haskins, C (ed.) 2007, *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities,* Version 3.1., INCOSE, San Diego, CA (US).

——— 2010, *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, Version 3.2., INCOSE, San Diego, CA (US).

Madni, A 2018, *Transdisciplinary Systems Engineering: Exploiting Convergence in a Hyper-Connected World*, Springer, Cham, Switzerland.

Payes, R 2017, ‘What Leonardo da Vinci Can Tell Us About STEM vs STEAM’, Accessed at What Leonardo da Vinci Can Tell Us About STEM vs STEAM - Innovation & Tech Today (innotechtoday.com)

Petroski, H 2012, ‘The Importance of Engineering History’, *International Engineering History and Heritage: Improving Bridges to ASCE’s 150th Anniversary*. American Society for Civil Engineers.

University of Central Florida 2023, ‘Comparing STEM vs. STEAM: Why the Arts Make a Difference’, Accessed at Comparing STEM vs. STEAM: Why the Arts Make a Difference | UCF Online

Unknown Author 2023, ‘Civil Inventions’, Accessed at Modern day Leonardo da Vinci - modern day inventions (leonardodavincisinventions.com)

Vervaeke, J 2018, ‘Cognitive Science Rescues the Deconstructed Mind’, Accessed at Cognitive Science Rescues the Deconstructed Mind | John Vervaeke | TEDxUofT - YouTube

Biography

Steven J. Simske. Dr. Simske received a post-Doctoral degree in Aerospace Engineering and a post-Doctoral degree in Electrical and Computer engineering from the University of Colorado. From 1994 to 2018, he was an engineer (HP Fellow since 2011), Vice President, and Director at HP Labs. Since 2018, he is a Faculty Professor of Systems Engineering at Colorado State University (CSU). He is the author of 500 publications and 240 US patents. His research interests include analytics, systems security, sensing, signal and imaging processing, printing and manufacturing, and situationally aware robotics. Dr. Simske is an IEEE Fellow, an NAI Fellow, an IS&T Fellow, and its former President (2017-2019). Steve completed a CSU Faculty Institute for Inclusive Excellence (FIIE) Fellowship in 2020 and was a CSU Best Teacher awardee in 2022. In his 20+ years in the industry, he directed teams to research 3D printing, education, life sciences, sensing, authentication, packaging, analytics, imaging, and manufacturing. He has written four books on analytics, algorithms, and steganography. At CSU, he has a cadre of on-campus students in Systems, Mechanical, and Biomedical Engineering and a larger contingent of online/remote graduate students researching various disciplines.

Pamela Vaughan Knaus. Dr. Knaus received a Ph.D. in Historical Studies in 1996 from Southern Illinois University with an emphasis on American immigration law and United States foreign policy. She joined the University Honors Program in 2009, and offers seminars that examine the United States in the 1960s, and America & Vietnam. Her History Department courses include “Pacific Wars: Korea and Vietnam” and “United States 1877-1917".

Rock Mendenhall. Rock Mendenhall is a Ph.D. candidate in the Department of Systems Engineering at Colorado State University. He has a Master’s in Applied Systems Engineering from the Georgia Institute of Technology. He also possesses certifications in Artificial Intelligence Management from Georgetown University and as a Lean Six Sigma Black Belt from Villanova University. His research interests include cognitive science, cognitive systems engineering, history, artificial intelligence, knowledge management, and continuous process improvement.

A time-constrained integration of Systems Thinking into generic engineering degrees: A case study from NZ working towards Washington Accord Accreditation)

1st Nick Pickering
School of Engineering
University of Waikato
Hamilton, New Zealand
Nick.Pickering@waikato.ac.nz

2nd Dr Ralf Schlothauer
School of Engineering
University of Waikato
Hamilton, New Zealand
ralf@whioinnovations.co.nz

***Abstract*—In New Zealand (NZ), there is a low awareness of Systems Engineering outside of the defence and transport domains. A drop in international students post COVID-19 has resulted in a tertiary education sector that is struggling financially. Under these constraints, it can at first appear unviable to integrate Systems Engineering into all undergraduate engineering degrees. Upon further analysis, it is found that many engineering schools within universities are striving to obtain and retain accreditation against the internationally recognised Washington Accord. The Washington Accord requires graduate competencies to be demonstrated across complex engineering problems with consideration for health, safety, cultural, societal, environmental, sustainability and ethical factors. These factors are to be applied while demonstrating knowledge and understanding of engineering management principles and economic decision-making to manage projects in multi-disciplinary environments. Based on this knowledge, the benefit of introducing Systems Engineering principles to all engineering students crystallises.**

The case study, from the University of Waikato in New Zealand, outlines the approach taken to introduce the concept of Systems Thinking in a time-constrained 2-week period with 189 first-year undergraduate students from across Civil, Environmental, Chemical, Materials, Mechanics, Mechatronics, Electrical/Electronics and Software Engineering programmes.

This paper describes the content and tools utilised to teach undergraduate engineering students to understand complex global issues and then identify innovative system interventions through the use of systems thinking. Future research is planned to identify the value of Systems Thinking within the teaching of the Washington Accord and UN Sustainable Development topics while developing open-source resources to accelerate adoption within time-constrained environments.

***Index Terms*—Education, Systems Thinking, Industry 4.0.**

I. Introduction

Currently, we are experiencing growth in the complexity of both Industry 4.0 technology and global challenges, as represented in the United Nations Sustainable Development Goals (UN SDG) [1]. To address the increasing complexity and demand for all disciplines of engineering to contribute to the UN SDGs, it would be desirable to provide Systems Engineering training to undergraduates.

Systems Engineering (SE) is a ”transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems using systems principles and concepts and scientific, technological and management methods” [2]. Systems Engineering can be represented by a group of competencies as outlined by the International Council Of Systems Engineering (INCOSE) in [3], spanning core, professional, management, technical and integrating competencies.

As a result of financial pressures across many academic institutes in NZ following COVID-19, there is pressure to reduce, not increase the number of papers taught at the undergraduate level. To combat this limitation, the approach selected for this study was to utilise Systems Thinking as a tool to meet and retain accreditation towards the Washington Accord [4]. There are many definitions of Systems Thinking, including but not limited to Checklands view of it being ”An epistemology which, when applied to human activity is based on four basic ideas: emergence, hierarchy, communication, and control as characteristics of systems” [4] or Senges perspective that Systems Thinking is ”a process of discovery and diagnosis – an inquiry into the governing processes underlying the problems and opportunities” or ”a discipline for examining wholes, interrelationships, and patterns utilizing a specific set of tools and techniques” [5].

The Washington Accord [4] is an internationally benchmarked standard for ”entry-level” engineering education competence from the International Engineering Alliance structured around 12 graduate attributes. These include engineering knowledge, problem analysis, design/development of solutions, investigation and research, modern tool usage, society, environment/sustainability, ethics, individual/teamwork, communication, project management/finance and life-long learning.

This research paper investigates whether Systems Thinking can be taught to 1st-year undergraduates in a time-constrained environment, to help solve real-world problems and contribute to accreditation against Washington Accord graduate attributes.

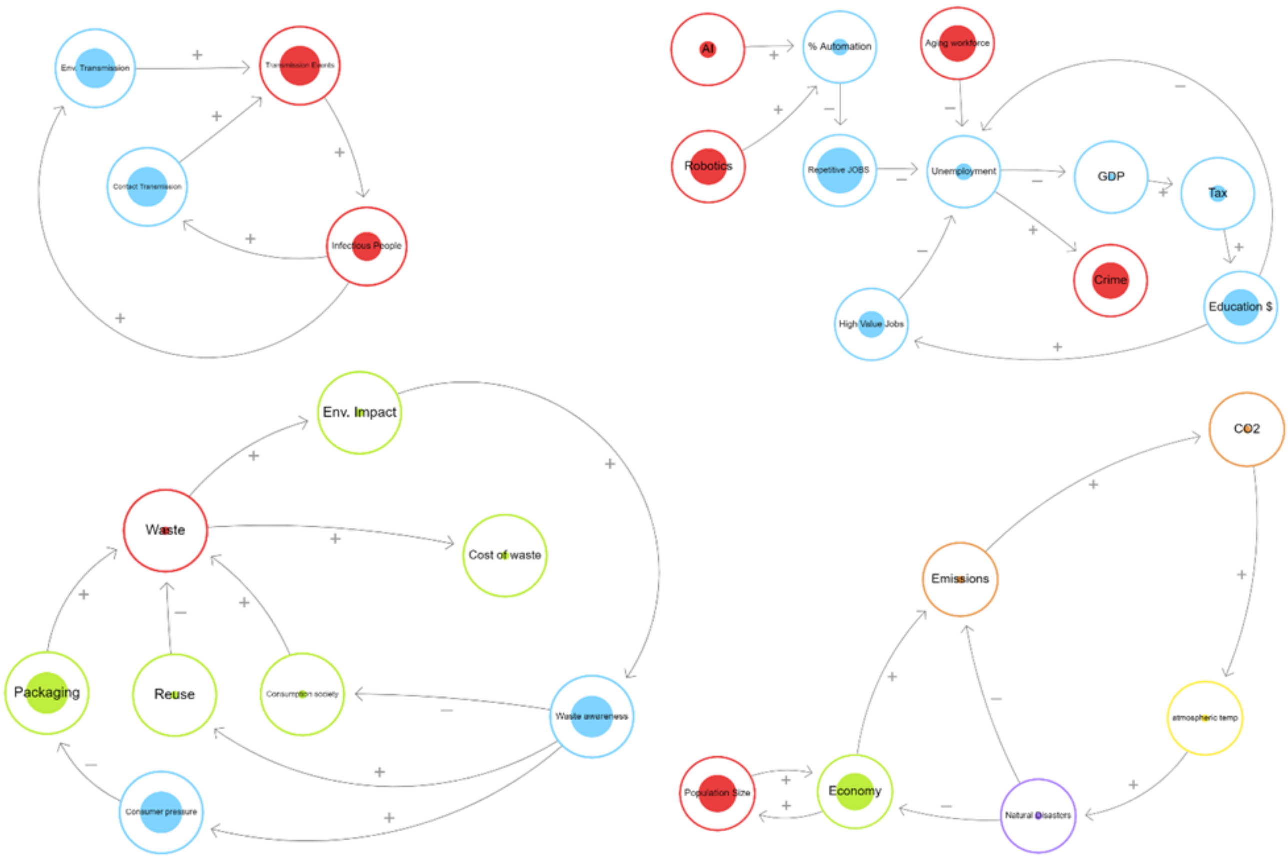


Fig. 1. Basic causal loop diagrams used to introduce the concept of Systems Thinking for UN SDGs

II. Method

The 2-week Systems Thinking module was delivered within a 12-week undergraduate engineering 15-point paper called "Engineering and Society" [6]. The module consisted of 4 x 50 minutes lectures, 2 tutorials and 3 x 2 hour workshops.

A. Week 1

Lecture 1 titled "Introduction to Systems" started with an overview of what a system is [6]–[10] along with examples backed up by holism concepts presented by Ackoff and analogies based on football teams at the world cup. Lecture 1 finished off with a short quiz to reinforce learning and homework to read up on the "Introduction to Systems Engineering Fundamentals" [11]. Lecture 2 went straight into teaching causal loop diagrams [5], [12] as a tool to analyse systems. As a result of the low level of engineering domain knowledge associated with first-year undergraduates, a nature-based example from Yellowstone National Park in the United States was utilised. The Yellowstone National Park example documenting how the re-introduction of wolves changed the behaviour of the elk, which in turn improved the whole ecosystem from the return of trees, stabilising riverbeds, cleaning the waterways and creating a habitat for beavers, birds and animals [13]. Due to the topical nature of COVID-19 back in 2020, causal loop diagrams based on a systems approach to preventing and responding to COVID-19 were presented and discussed [14] to demonstrate notation. The week 1 workshop consisted of working in groups of 10 around a large touchscreen and being led by the tutors through the creation of causal loop diagrams in a free online tool called loopy [15]. The exercise started with base components and worked through system relationships within the global challenges of global warming, unemployment, COVID-19 and solid waste, Fig. 1. For each of the challenges, students were then asked to brainstorm potential interventions and assess their impact against a newly created Systems Canvas, Fig. 2. The Systems Canvas was created as a visual checklist to bridge the knowledge gap for undergraduates and provide a prompt for discussion on potential inputs and outputs in terms of social systems (institutions, human systems, companies and communities), natural systems (climate, biological and natural resources), infrastructure, economics, technology, digital, waste (in terms of lean thinking [16]), viability, product desirability and UN SDGs.

Now that the students had a base introduction to systems and systems thinking, with hands-on practice of how to model systems from the workshop, the week 1 tutorial tested students

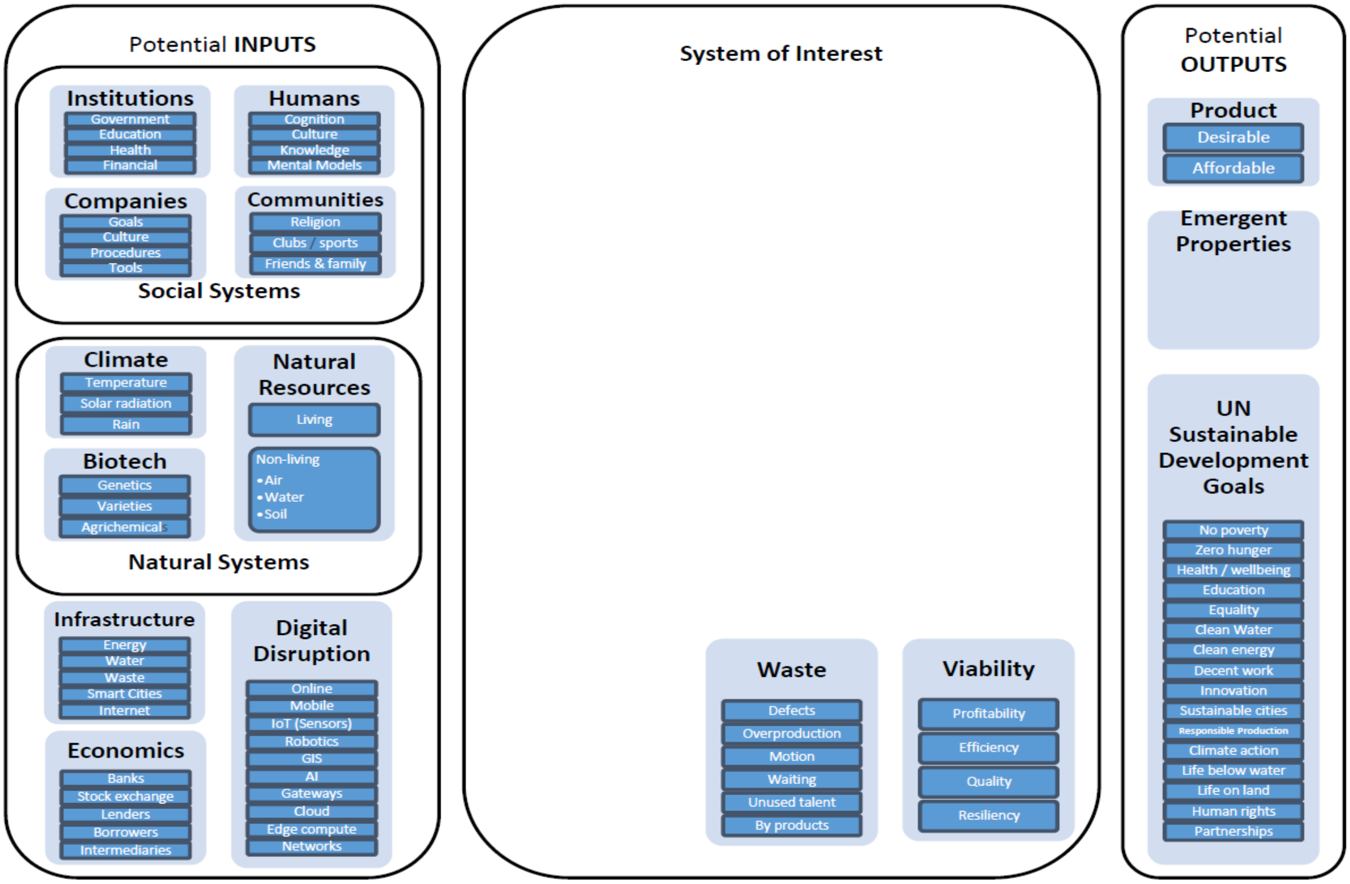


Fig. 2. Systems Canvas as a checklist for identifying and assessing impact from a system intervention

on causal loop diagram notation, loops and delays. This test was followed by an exercise to explain the limitations of loopy, specifically the inability to model the actual systems dynamics of relationships. This was demonstrated through an exercise in identifying interventions engineers could contribute to using the Climate Change Solutions Simulator EN-ROADS [17] to reduce temperature increases.

B. Week 2

Week 2 started with lecture 3, introducing complex problems through causal loop diagrams. Problems explored during the lecture included COVID-19 [14], [18], agriculture environmental impacts [19], staff turnover [20] and soil salinity [21]. The lecture then focused on a structured process to map out a causal loop diagram using city centre traffic as an example to work through together:

1) Research the topic, initially using UN SDG [1],
2) Identify the components, using the Systems Canvas as an initial checklist for potential stocks and flows not identified during the research.
3) Establish key relationships,
4) Identify existing loops (reinforcing and balancing),
5) Identify potential interventions creating new loops (reinforcing and balancing),
6) Test, prioritise and improve with Subject Matter Experts (SME) and stakeholders.

Lecture 3 operated to reinforce the creation of causal loop diagrams focusing on common mistakes and introducing the concept of emergent properties. Emergent properties were taught leveraging quality attributes described in [22] and the ISO/IEC25010 Systems and software Quality Requirements and Evaluation (SQuaRE) [23]. The week 2 workshop introduced the use of causal loop diagrams to understand complex engineering problems. The students were tasked with watching a video on the Boeing 737 Max disasters [24] and an IEEE Spectrum article [25], while using the previously taught Systems Canvas (Fig. 2) to identify potential factors. The students split into teams of 5 and were tasked to complete causal loop diagrams, in loopy, spanning the themes of economics, aircraft control, human factors and the Boeing 737 max Maneuvering Characteristics Augmentation System (MCAS), (Fig. 3).

- **Economic:** Components starting with Ticket price, Demand, Revenue, Profit, Operating cost, Fuel cost, Engine efficiency and Cost to buy new aircraft
- **MACS:** Components starting with Aircraft thrust, Angle of attack sensor, Risk of stall, MACS intervention and Tailplane angle pitch.

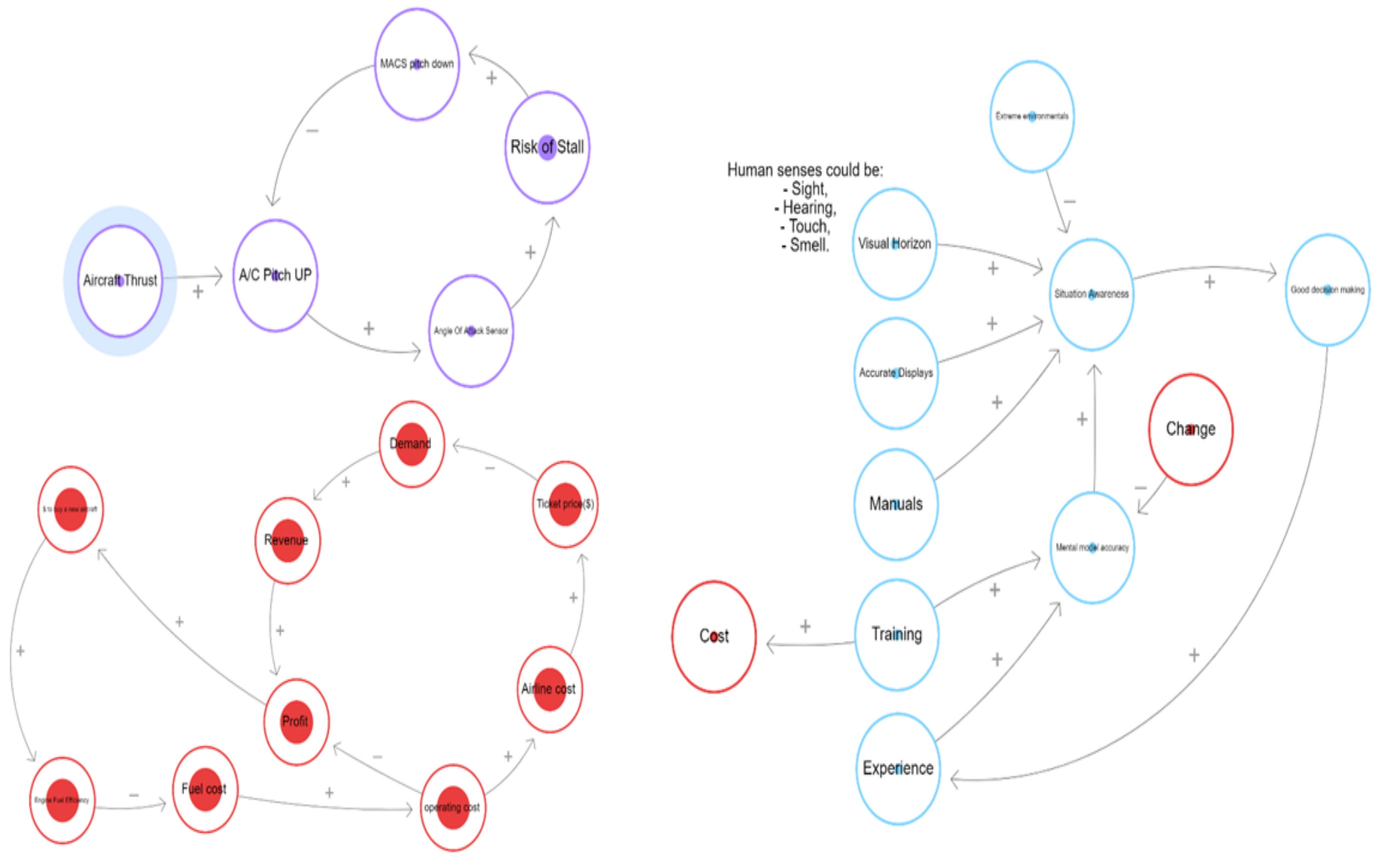


Fig. 3. Causal loop diagram to assist first-year engineering students understand the Boeing 737 Max disasters

- **Human Factors:** Components starting with Training, Cost, Pilot experience, Pilot mental model accuracy, Situation awareness, Manuals, Accurate displays, Visual horizon, Change and Good decision making.

To close out week 2, each group presented to the wider workshop their reflections on the design, design process, sensor redundancy, human factors, ethics and economic pressures impacting the disasters. Students were finally tasked with an assignment to write a formal letter about the disaster, including suggested interventions and mitigation techniques.

C. Week 3

Week 3 lectures progressed onto the next module within the paper, but the workshop time was utilised to follow the structured process, Systems Canvas and causal loop diagram approach to map out their selected group project, associated with a challenge outlined within the UN SDGs. The tutorial time was utilised to run through research techniques and how to assess the reliability of sources.

III. Results

The results of the 2-week training module on Systems Thinking are measured in the subjective assessment of the innovation level of the groups UN SDG system interventions and the traceability of the content to the Washington Accord graduate attributes.

A. Interventions to UN SDG Challenges

An informal subjective assessment of the system interventions were performed by the authors. Four categories of innovation were marked relative to the first-year level of study:

- **Poor innovation:** Idea not novel.
- **Adequate innovation:** Adequate innovation but with financial viability, technical feasibility or user desirability issues.
- **Good innovation:** New or solid intelligent incremental improvement that is financial viability, technical feasibility and desirable for users.
- **Excellent innovation:** Highly innovative and unique. No similar concept exists within New Zealand.

From a total of 35 groups, consisting of 189 students, the innovation levels were subjectively assessed as one being poor, nine adequate, sixteen good and nine excellent, Fig. 4.

Examples of innovative system interventions for first-year undergraduate engineering students can be seen below:

1) Algae production to reduce dairy contamination at river outlets with fertilizer as a by-product.

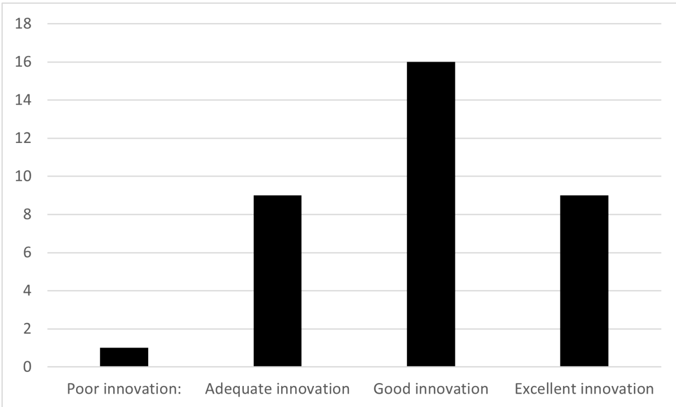


Fig. 4. Count of innovation assessment per group

2) Mobile application-based incentivisation scheme for consumers to record recycling of materials commonly ending up in our oceans.
3) Modular solar-powered desalination plants to slow desertification in parts of Southern Australia.
4) Water usage awareness and incentivisation to address water shortages in Auckland New Zealand.
5) Fibre-based 3D printing of low-density housing to address construction and labour cost challenges.
6) Modular instrumented vegetable growing pods to reduce packaging and food waste targeted at consumers with limited time or knowledge to grow their own.
7) School-based car pooling app to address traffic congestion around schools while alleviating traditional concerns with app security.
8) Processing of waste tyres into building materials.
9) Measurement and gamification of company emissions by an independent entity to provide a marketable benefit to sustainable practise.
10) Virtual Reality (VR) based simulation game to change social attitudes to poverty.
11) Virtual Reality (VR) based training to upskill factory workers with automation skills.

B. Washington Accord Traceability

The time-constrained integration of Systems Thinking teaching module is traced to the Washington Accord graduate attributes in Table I.

TABLE I
WASHINGTON ACCORD GRADUATE ATTRIBUTES TRACED TO TIME-CONSTRAINED SYSTEMS THINKING TEACHING BLOCK

No.	Graduate Attribute	Traceability
WA1	Engineering knowledge	Not applicable.
WA2	Problem analysis	Research, analyse and solve complex UN SDG problems.
WA3	Design / development of solutions	Design for open-ended problems with awareness of safety risks associated with Boeing 737 Max disasters.
WA4	Investigation and research	Research into UN SDG.
WA5	Use of modern engineering tools	Understanding the limitation of modelling tools.
WA6	The engineer and society	Understanding of impact, both positive and negative, engineers can have on society through UN SDG and Boeing 737 Max workshops.
WA7	Impact of engineering on society and the environment	The ability to analyse complex economic, social, environmental and safety aspects.
WA8	Ethics and equity	Awareness of ethics from Boeing 737 Max disaster workshop.
WA9	Individual and teamwork	Teamwork during project deliveries.
WA10	Communication skills	Verbal presentations during workshops, visual communication during poster assessment and written communication within the project report.
WA11	Economics and project management	Awareness of the economic pressures through analysis of the Boeing 737 Max disaster.
WA12	Life-long learning	Students taught how to research.

IV. DISCUSSION

Assessing the time-constrained integration of systems thinking into generic engineering programmes for first-year undergraduates can be viewed from a component and a holistic system level. From a component level, issues can be identified in the short 50-minute introduction on systems, the focus on causal loop diagrams as an analysis tool (excluding all other techniques), the use of loopy as a modelling tool with system dynamics limitations and the simplification of both the UN SDG challenges (Fig. 1) and the Boeing 737 Max disasters (Fig. 3). Issues could also be identified in the Systems Canvas, Fig. 2, not being complete and the subjective assessment of innovation levels.

From a holistic system perspective, first-year undergraduates with students from across Civil, Environmental, Chemical, Materials, Mechanics, Mechatronics, Electrical/Electronics and Software Engineering programmes were introduced to Systems Thinking. The long-term value of the integration of Systems Thinking modules early on in the tertiary education process is difficult to quantify. Notwithstanding the difficulty in quantifying value, the study has found that through the teaching of systems, systems thinking, causal loop diagrams and the Systems Canvas as a checklist, first-year engineering students are able to create innovative solutions that take into account social, environmental, ethical and human factors.

V. CONCLUSION

The study aimed to assess the value of teaching Systems Thinking to first-year undergraduates in a time-constrained environment. The innovation assessment results, Fig. 4, demonstrated that Systems Thinking can add value to empower students to not only understand the complexity of the social, environmental, safety, ethical and economic challenges demanded in the Washington Accord graduate attributes but also arm them with the capability to identify appropriate innovations and interventions at a system or system of systems level. The traceability of the Systems Thinking module to the Washington Accord graduate attributes demonstrates how the programme leaders with limited knowledge of Systems Engineering can see the value in the introduction of a short Systems Thinking module to support accreditation activities.

VI. RECOMMENDATIONS AND FUTURE WORK

In this paper, we have explored the potential for Systems Thinking in a time-constrained environment. Based on the investigation, we recommend the following future work and research directions:

1) Review and baseline this study against other time-constrained teachings of Systems Thinking.
2) Survey stakeholders to identify the sentiment towards the development of open-source Systems Thinking resources and tools to address UN Sustainable Development Goals.

ACKNOWLEDGMENT

The studies within this work were supported by the School Of Engineering, University of Waikato, New Zealand.

REFERENCES

[1] U. Nations, "Envision2030: 17 goals to transform the world for persons with disabilities," 2020. [Online]. Available: https://www.un.org/development/desa/disabilities/envision2030.html

[2] International Organisation for Standardisation (ISO), "Iso/iec/ieee 15288:2023 systems and software engineering – system life cycle processes," International Organisation for Standardisation, Report, 2023.

[3] International Council on Systems Engineering (INCOSE), "Systems engineering competency framework," Report, 2018. [Online]. Available: https://www.incose.org/docs/default-source/professional-development-portal/isecf.pdf?sfvrsn=dad06bc7_4

[4] International Enigneering Alliance, "25 years washington accord," 2014. [Online]. Available: https://www.ieagreements.org/assets/Uploads/Documents/History/25YearsWashingtonAccord-A5booklet-FINAL.pdf

[5] P. M. Senge, *The fifth discipline: The art and practice of the learning organization*. Broadway Business, 2006.

[6] University of Waikato, "Engen170-20b (ham) engineering and society paper outline," Report, 2020. [Online]. Available: https://paperoutlines.waikato.ac.nz/outline/ENGEN170-20B%20(HAM)

[7] ISO/IEC/IEEE, "Iso/iec/ieee 15288:2015 systems and software engineering – system life cycle processes," International Organisation for Standardisation / International Electrotechnical Commissions / Institute of Electrical and Electronics Engineers, Report, 2015.

[8] J. Boardman and B. Sauser, *Systems thinking: Coping with 21st century problems*. CRC Press, 2008.

[9] D. Dori, *Object-Process Methodology: A Holistic Systems Paradigm; with CD-ROM*. Springer Science Business Media, 2002.

[10] R. A. Johnson, F. E. Kast, and J. E. Rosenzweig, "Systems theory and management," *Management Science*, vol. 10, no. 2, pp. 367–384, 1964.

[11] International Council on Systems Engineering (INCOSE), "Systems engineering body of knowledge," October 16 2018. [Online]. Available: https://www.sebokwiki.org/wiki/Download_SEBoK_PDF

[12] D. H. Meadows, *Thinking in systems : a primer*. White River Junction, Vt.: White River Junction, Vt. : Chelsea Green Pub., 2008, includes bibliographical references (pages 208-210) and index.

[13] BBC, "How reintroducing wolves helped save a famous park," 07/07/23. [Online]. Available: https://www.bbc.com/future/article/20140128-how-wolves-saved-a-famous-park

[14] D. T. Bradley, M. A. Mansouri, F. Kee, and L. M. T. Garcia, "A systems approach to preventing and responding to covid-19," *EClinicalMedicine*, vol. 21, 2020.

[15] N. Case, "Loopy: A tool for thinking in systems," 2023. [Online]. Available: https://ncase.me/loopy/

[16] J. P. Womack and D. T. Jones, "Lean thinking—banish waste and create wealth in your corporation," *Journal of the Operational Research Society*, vol. 48, no. 11, pp. 1148–1148, 1997.

[17] L. S. Siegel, J. Homer, T. Fiddaman, S. McCauley, T. Franck, E. Sawin, A. P. Jones, J. Sterman, and C. Interactive, "En-roads simulator reference guide," Technical Report, Report, 2018. [Online]. Available: https://img.climateinteractive.org/2021/06/En-ROADS_Reference_Guide_052721.pdf

[18] R. M. Anderson, H. Heesterbeek, D. Klinkenberg, and T. D. Hollingsworth, "How will country-based mitigation measures influence the course of the covid-19 epidemic?" *The lancet*, vol. 395, no. 10228, pp. 931–934, 2020.

[19] B. K. Bala, F. M. Arshad, and K. M. Noh, "System dynamics," *Modelling and Simulation*, vol. 274, 2017.

[20] A. Hidayatno, A. R. Destyanto, A. O. Moeis, M. Rizky, and N. Iman, "Scenario planning using system dynamics for reducing uncertainty on managing employee turnover," in *Proceedings of the 2nd Asia-Pacific Region System Dynamics Conference, Singapore*, Conference Proceedings, pp. 19–22.

[21] A. Inam, J. Adamowski, J. Halbe, and S. Prasher, "Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: A case study in the rechna doab watershed, pakistan," *Journal of environmental management*, vol. 152, pp. 251–267, 2015.

[22] T. Bianchi, D. S. Santos, and K. R. Felizardo, "Quality attributes of systems-of-systems: A systematic literature review," in *2015 IEEE/ACM 3rd International Workshop on Software Engineering for Systems-of-Systems*, Conference Proceedings, pp. 23–30.

[23] ISO/IEC, "Iso/iec 25010:2011 systems and software engineering — systems and software quality requirements and evaluation (square) — system and software quality models," 2011. [Online]. Available: https://www.iso.org/standard/35733.html

[24] Vox, "The real reason boeing's new plane crashed twice," 2019. [Online]. Available: https://youtu.be/H2tuKiiznsY

[25] G. Travis, "How the boeing 737 max disaster looks to a software developer," *IEEE Spectrum*, vol. 18, 2019.

Fumbling towards net-zero carbon policies: using simulation to test understanding of systems thinking principles

C A Browne, The Australian National University. Chris.Browne@anu.edu.au

Abstract

This paper presents the results of an experiment utilising different forms of simulation to explore understanding of systems thinking principles. The experiment is based in the context of the carbon cycle, where stocks of carbon, such as the accumulation of carbon in the atmosphere, are modified through flows, the exchange of carbon between stocks. Participants were given basic information about the Earth's carbon cycle, including graphs of the historical record of atmospheric carbon concentrations and annual rate of emmisions. Participants were randomly assigned a sequence of three simulation activities—a computer simulation, a mental simulation and a physical simulation—and were invited to correctly chart a trajectory of the annual rate of emmissions required to reach net zero in a pre-test and after each activity. The results suggest that exposing participants to different simulation approaches can improve understanding, but also highlights that participants are also not readily able to change incorrect responses.

Background

The Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC, 2023) outlines five shared socio-economic pathways for scenarios of future carbon emissions, with emissions scenarios based in the scientific literature that range from low (~1.9℃) to high (~8.5℃) increase to global mean temperature by the end of this century. The emissions pathways required to keep temperature increases to a minimum require a dramatic reduction in emissions, reversing the direction of the current trajectory, shown in Figure 1 (left). Although nations have been making pledges to reduce emissions for decades, the trajectory of global emissions continues to move in a direction that do not meet simple accumulation principles.

The climate system is complex, with multiple dynamic feedback effects that influence Earth's biophysical systems. For the purposes of this study, a simplified 'carbon budget' model employed to help communicate the stocks and flows of carbon system was explored, shown in Figure 1 (right). Of particular importance to this study is the relationship between natural and anthropogenic emissions of carbon exchanges between the atmospheric stock and the aggregate terrestrial (i.e ocean, soils, vegetation, et cetera) stocks, similar to that described in the 'carbon bathtub' (Holmes in Kuznig, 2009). The simple learning of the bathtub model is that if the rate of inflows exceeds the rate of outflows—as carbon emissions exceeds removals—the water in the bathtub will increase.

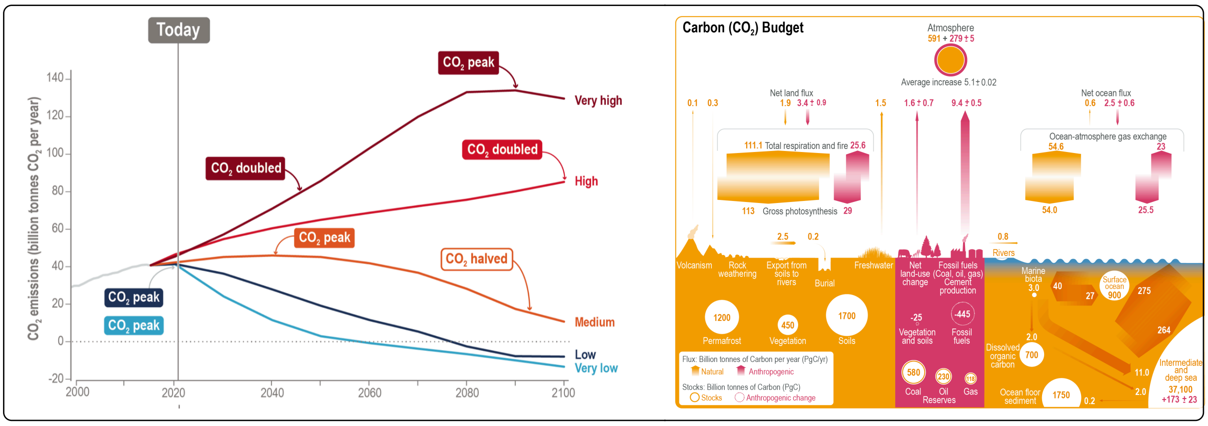


Figure 1: (left) future emissions trajectories that demonstrate potential futures outlined in IPCC shared socio-economic pathways (SSP) 1 (very low) to 5 (very high). (right) carbon fluxes between natural stocks, including anthropogenic effects (IPCC, 2021).

It has been well established in the literature that participants are often confused in quantitative systems thinking tasks, such as stock-and-flow dynamics (Booth Sweeney & Sterman, 2000; Sterman & Booth Sweeney, 2002; 2007; Cronin & Gonzalez, 2007; Cronin *et al*, 2009; Brockhaus *et al*, 2013; Sedlmeier *et al*, 2014). Previous work shows that when given a graph of a stock, such as the stock of carbon in the atmosphere, only 1 in 5 participants can accurately draw the trajectory for the rate of change (Sterman and Booth Sweeney, 2002). Introduction of group discussions and written descriptions accompanying graphical charts can improve this result to over 4 in 5 correct responses (Browne, 2015).

This paper further responds to Sterman's (2008) challenge to explore new methods to develop intuitive systems-thinking capabilities so that people can discover, for themselves, the dynamics of systems and impact of policies. This paper explores whether scaffolded exposure to different modes of simulation in a group setting can help people's understanding of systems-thinking capabilities.

Methodology

A workshop was undertaken with 78 undergraduate students in an introductory environmental science class during six occurances of regular tutorials. Participants were given an activity briefing, which included definitions, a visualisation of the global carbon budget, proposed trajectories for future pathways, a chart of historical atmospheric carbon and the context for the activity, and then were issued a pre-test question based on Sterman and Booth Sweeney, updated to the context for IPCC's Shared Socio-economic Pathway (SSP) 2 "Middle of the Road" scenario, where the atmospheric carbon concentration levels off at 600 parts per million by the end of the century. Participants had approximately five minutes to complete this task shown in Figure 2.

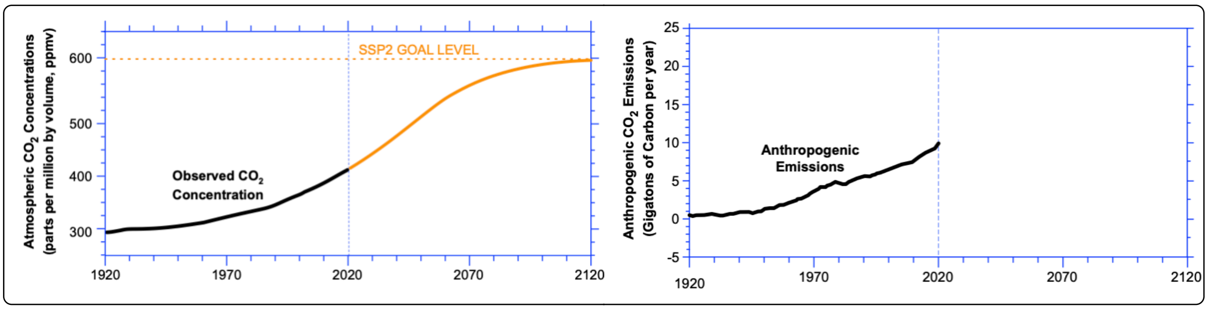


Figure 2: Graphical response task. (left) The black line represents the observed atmospheric CO2 concentrations. The yellow line is a projected scenario that stabilises atmospheric CO2 concentrations to 600ppm as per SSP2. (right) the task that the participants completed (charting the right-hand side) based on Sterman and Booth Sweeney (2002).

After completion of the pre-test, participants were randomly assigned groups and completed three simulation activities in each of the six possible different sequences: a computer simulation, a mental simulation, and a physical simulation. Groups worked through an equivalent series of written prompts to guide the interaction for each simulation activity, and were given the opportunity to revise their previous response after each activity. Participants were encouraged to discuss the context of the activities, but to not share their answers during the activities. Groups were given approximately five minutes to complete each activity, and then two minutes to revise responses between each activity.

The computer simulation employed the C-ROADS simulator (Climate Interactive, 2023), with participants prompted to adjust global emissions through three variables—emissions peak year, reductions begin year and annual reduction year—given the CO_2 concentration history and the resulting future trajectories. The mental simulation task employed a model of the 'carbon bathtub', and prompted participants to consider first how to achieve dyamic equilibrium—where the additions and removals are approximetely equal—and then are altered by the anthropogenic peterbation. The physical simulation activity required participants to physically pump water between two tubs which reprented the exchange of carbon between the atmospheric and terrestrial stocks, and asked participants to model dynamic equalibrium and then the anthropogenic peterbation. After all activities were completed, a small, open-ended discussion was held to draw connections between the activity and the coursework they were undertaking.

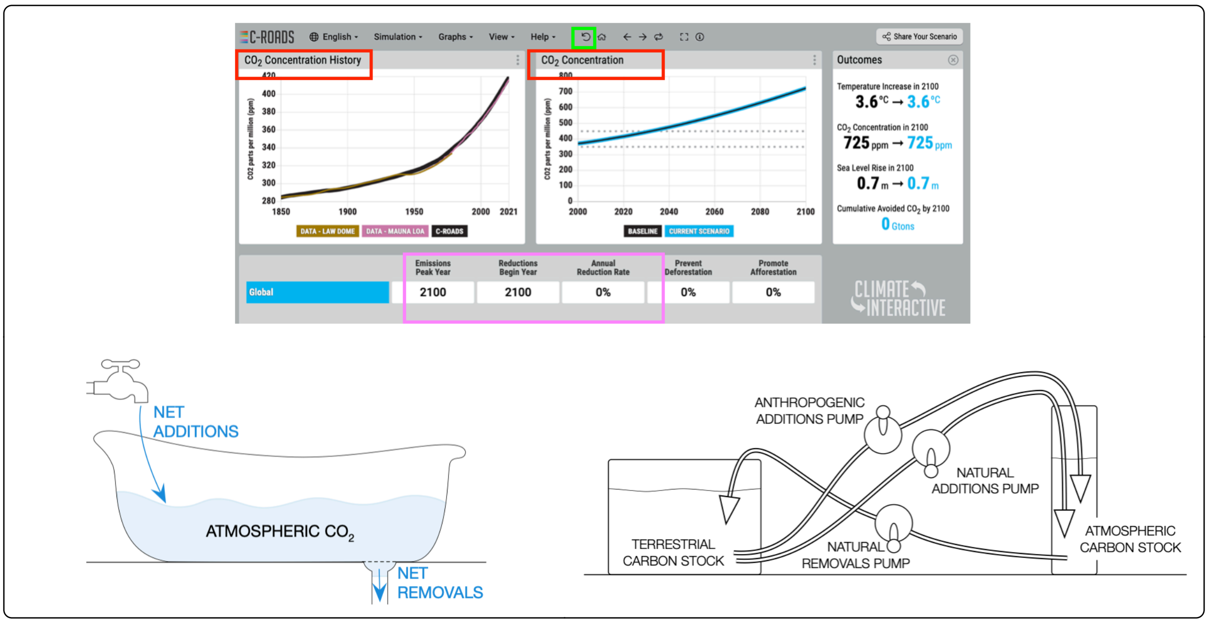


Figure 3: Figures from worksheets given to participants. (Top) C-ROADS simulation settings used in the computer simulation activity (C-ROADS 2023); (bottom left) a representation of the carbon bathtub used in the mental simulation; (bottom right) a diagram of the physical pumps and tubs used in the physical simulation.

The graphical responses were coded into six descriptions related to the shape of the plotted trajectory, which were later categorised into three broad groups. This provided the basis for comparison between activity types and over simulation rounds. These descriptions and their codings are shown in Table 1.

Category	**Reduced Emissions**	**Similar Emissions**	**Increased Emissions**
Descriptions	- Decrease to above/at/below zero - Stabilise at lower level	- Increase then decrease - Stabilise at current level	- Stabilise at higher level - Increase

Table 1: Categories and descriptions of graphical responses used in the analysis of results

Results

Table 2 shows the number of participants in each sequence. Of the 78 participants, 4 did not complete a graphical response in the pre-test, and 1 participant did not complete a graphical response in any of the activities. The variation between group sizes can be attributed to the group dynamics within a real-world tutorial environment.

Activity/Sequence	**Activity Round 1**	**Activity Round 2**	**Activity Round 3**	Total (n)
Computer Simulation	26 (2)	25 (1)	26	77
Mental Simulation	27 (1)	26 (1)	24 (1)	77
Physical Simulation	24	26 (1)	27 (2)	77
Total (n)	77	77	77	**231**

Table 2: Count of participants in each treatment group. Numbers in brackets represent participants that did not complete a graphical response in the pre-test.

The type of simulation and the sequence of the simulation are both factors that could contribute to the interpretation of results. Table 3 shows a summary of results from the pre-test and then each round of activity and each simulation type. Approximately 20% of participants in the pre-test plotted a trajectory which would move emissions towards the stated goal of meeting SSP2 by reducing annual emissions to zero. This improved to approximately 36% after participants had completed all three activities. All three modes of simulation demonstrated similar results, with between 28-32% of responses showing a trajectory that could approximately meet the stated goal.

Activity/Response	**Reduced Emissions**	**Similar Emissions**	**Increased Emissions**	**Total**
Pre-Test	15 (20%)	12 (16%)	47 (63%)	74
Computer Simulation	23 (30%)	15 (20%)	39 (51%)	77
Mental Simulation	22 (29%)	17 (22%)	38 (49%)	77
Physical Simulation	25 (32%)	15 (20%)	37 (48%)	77
after Activity Round 1	21 (27%)	11 (14%)	45 (58%)	77
after Activity Round 2	21 (27%)	20 (26%)	36 (47%)	77
after Activity Round 3	28 (36%)	16 (21%)	33 (43%)	77

Table 3: Results by emissions trajectory for each simulation activity and after each simulation activity. Rows may not total 100% due to rounding.

The simulation activities were designed to allow participants to explore and test their understanding of the given scenarios, and revise their responses if needed. Table 4 shows the relative changes in response after each activity by simulation type and activity round. In the majority (between 67-77%) of cases, participants did not change their responses between rounds. When participants did change their response, it was more likely to demonstrate an improving understanding (between 17%-23%) rather than a worsening understanding (between 5-10%). Of the three simulation activities, the physical simulation was most likely to prompt a change in response, but accounted for the highest likelihood of both improving and worsening understandings.

Activity/Response	**Improve**	**No change**	**Worsen**	**Total**
Computer Simulation	13 (17%)	58 (76%)	5 (7%)	76
Mental Simulation	14 (18%)	59 (77%)	4 (5%)	77
Physical Simulation	18 (23%)	52 (67%)	8 (10%)	77
after Activity Round 1	14 (19%)	53 (72%)	7 (9%)	74
after Activity Round 2	16 (21%)	57 (73%)	5 (6%)	78
after Activity Round 3	15 (19%)	58 (74%)	5 (6%)	78

Table 4: Count of participants changing response by simulation type and activity per activity round (not cumulative). Rows may not total 100% due to rounding.

Written responses were gathered alongside the graphical responses. This provides some insight into the participant's understanding, and also allows for triangulation between the graphical and written responses. The written responses were coded in relation to the graphical responses under the categories: 'match', 'mismatch' and 'partial match'. A 'match' response demonstrates a consistency between the written and graphical responses, whereas a 'mismatch' demonstrates an inconsistency. A 'partial match' blends responses or discusses multiple behaviours. Table 5 shows the responses during the pre-test. Of note is that for the increased emissions graphical responses, similar numbers of participants provided a matched (27%) or mismatched (28%) written response.

Graphical/Written	**Match**	**Mismatch**	**Partial Match**	Total
Reduced Emissions	13 (18%)	1 (1%)	1 (1%)	15 (20%)
Similar Emissions	10 (14%)	0 (0%)	2 (3%)	12 (16%)
Increased Emissions	20 (27%)	21 (28%)	6 (8%)	47 (64%)
Total	43 (58%)	22 (30%)	9 (12%)	74 (100%)

Table 5: Relationships between written and graphical responses. Columns and rows may not total 100% due to rounding.

Discussion

For a generation of participants who have been exposed to the recent climate debates and the concept of net zero, these results should be a cause for alarm for environmental science and systems thinking educators at all levels. Further, the low count of responses that identify a path to zero emissions should challenge us to consider how we can help to correct these straight-forward misunderstanding not only with students but the broader population.

The results show that, when given the opportunity to explore different modes of simulation, there remains broad confusion between the relationships between accumulations (stocks of carbon in the atmosphere) and rates of change (emissions, flows of carbon into the atmosphere), with only approximately 20% of participants drawing a correct graphical response in the pre-test, and only modest improvement to 36% after undertaking three different modes of simulation.

Sterman and Booth Sweeney (2002) concluded that a correlation heuristic—where the flow rates are correlated to the stock levels—is a possible cause for this result. Similar conclusions could be drawn from these results, with only 20% of participants in the pre-test showing a graphical response that would reverse the trajectory of emissions. Browne (2015) shows that this correlation heuristic relates specifically to the graphical responses, with written responses often not matching the graphical respresentation. Again, results demonstrate similar findings, with the increased emissions graphical responses divided between matching and mismatching responses.

In this experiment, a possible reason for the high rates of incorrect responses could be attributed to a form of anchoring bias. A large proportion (30%) of participants did not change increasing responses after any of the activities. The pre-test and final test results suggest that self-guided simulation activities can help people improve their understanding of stock-flow systems, with an increase in results that demonstrate a correct understanding of stock-flow relationships. Further work would be required to test whether more scaffolding or awareness–raising at the beginning of such an experiment would lead to an improved set of results in the pre-test and subsequent activities.

A final insight from delivering this experiment comes from anectdotal observations while groups of participants worked through the simulation activity. In many instances, participants had an 'aha' moment during a simulation that prompted a change in a response. For example, noticing that the units were different on the axes for the computer simulation, recognising the difference between the stocks and flows in the bathtub simulation, and seeing the water rise in the physical pumps set up. Once the 'aha' moment happened, it was clear to witness a renewed understanding of the stock-and-flow system and the magnitude of the change required to achieve the stated shared socio-economic pathway. Further work is required to explore how we can equip students with the capability to overcome these systems thinking traps and reach the 'aha' moment in their daily lives.

Conclusion

This paper describes a systems-thinking experiment that explored whether different modes of simulation could help overcome previously demonstrated systems-thinking traps. Similar phenomena were observed in line with previous studies, and it was found that the scaffolded simulation activities involving computer, mental and physical simulation all showed similar modest improvement of 9-12% improved responses with respect to the pre-test result of 20% correct responses. The improvement factor that yielded the highest result of 16% improvement from the pre-test was undertaking all three simulation modes, suggesting that the best approach to simulation is to provide a variety of simulation modes to inform systems-thinking sensibility.

References

Brockhaus, F., Arnold, J., Schwarz, M. & Sedlmeier, P., 2013, 'Does the modification of the representation format affect stock-flow-thinking?' *Proceedings of the 2013 International System Dynamics Conference,* System Dynamics Society, Albany, NY

Browne, C., 2015, A double-loop learning approach to construct understanding of accumulation principles, [PhD thesis, The Australian National University], Open Access Theses, http://hdl.handle.net/1885/101286

Climate Interactive, 2023, *The C-ROADS Climate Change Policy Simulator.* Available at: https://www.climateinteractive.org/c-roads/

Cronin, M.A, & Gonzalez, C., 2007, 'Understanding the building blocks of system dynamics'. *System Dynamics Review*, 23(1), 1–17.

Cronin, M.A., Gonzalez, C. & Sterman, J.D., 2009, 'Why don't well-educated adults understand accumulation? A challenge to researchers, educators, and citizens, *Organizational Behavior and Human Decision Processes*, 108(1), pp. 116-30.

IPCC, 2021: *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, doi:10.1017/9781009157896.

IPCC, 2023: AR6 *Synthesis Report: Climate Change 2023 Longer Report.* Sixth Assessment Report of the Intergovernmental Panel on Climate Change (in press).

Kuznig, R., 2009, 'The Carbon Bathtub', *National Geographic*, viewed 12 July 2023 at https://web.archive.org/web/20141018184541/http://ngm.nationalgeographic.com/big-idea/05/carbon-bath

Sedlmeier, P., Brockhaus, F. & Schwarz, M. 2014, 'Visual integration with stock-flow models: How far can intuition carry us?' in P Bender, R Hochmuth, PR Fischer, D Frischemeier & T Wassong (eds), *Mit Werkzeugen Mathematik und Stochastik lernen - Using Tools for Learning Mathematics and Statistics,* Springer Fachmedien Wiesbaden, Wiesbaden.

Sterman, J.D., 2008, 'Risk communication on climate: mental models and mass balance,' *Science*, 322(5901), pp. 532-3.

Sterman, J.D. & Booth Sweeney, L., 2002, 'Cloudy skies: assessing public understanding of global warming', *System Dynamics Review*, 18(2), pp. 207-40.

Sterman, J.D. & Booth Sweeney, L., 2007, 'Understanding public complacency about climate change: Adults' mental models of climate change violate conservation of matter', *Climatic Change*, 80(3-4), pp. 213-38.

Proposal of a Method to Foster Systems Thinking Using Visual Thinking Strategies

Akihiro Kitahara[1], Makoto Ioki[2]

[1] The System Design and Management Research Institute, Graduate School of System Design and Management, Keio University

[2] Graduate School of System Design and Management, Keio University

Visual Thinking Strategies (VTS) is a well-known method in art education. This presentation proposes a new method to foster systems thinking by applying VTS.

Problem

- Systems thinking is acquired through cross-functional work experience.
- However, it is siloed in the corporate world.
- Engineers are exposed to vertical organizational barriers, fragmented work, and strict deadlines.
- Project Based Learning is great, but it is time-consuming and burdensome.
- New methods are needed to foster systems thinking.

Objectives

- We propose a new method to foster systems thinking.
- The new method should increase engineers' engagement in systems thinking.
- The new method should encourage engineers to use systems thinking.
- The new method should be interesting and less burdensome for engineers.

Methods of VTS for Systems Thinking

Why VTS?

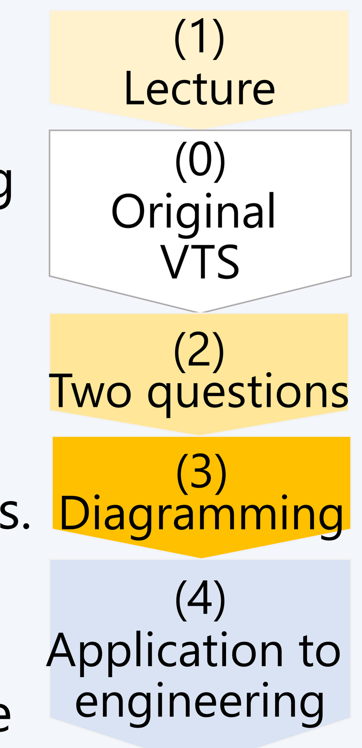
- VTS was developed by Philip Yenawine, the Museum of Modern Art (MoMA).
- In VTS, the facilitator leads observation and asks three simple questions. (Yenawine 2013)
  "What's going on in this painting?"
  "What makes you say that?"
  "What else can we find?"
- Moeller et al. (2013) pointed out that "participants use systems thinking to analyze the interaction of parts in a whole in VTS."
- Some applications outside the field have been reported, e.g., the medical field (Reilly et al. 2005).

Concept

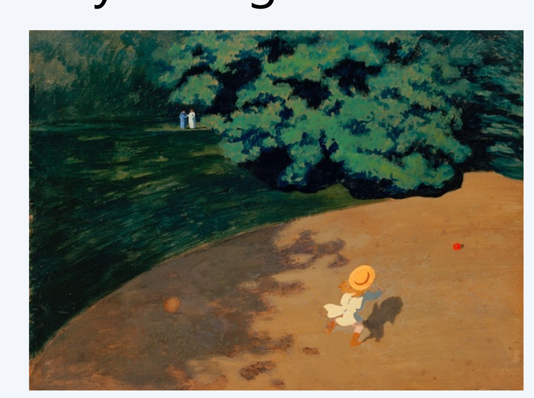
Add the following process to the original VTS.

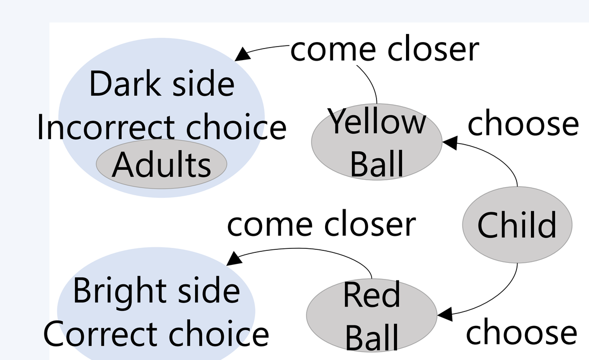
(1) Recognize a painting as a System.
(2) Add questions to VTS to make participants use more systems thinking.
(3) Use the system diagram as a reflection tool to bridge to engineering.
(4) Allow participants to experience that the same methods can be applied to engineering systems.

Details



(1) Lecture: explain the definition of a system and that a painting is one of the systems.
(2) Two additional questions: analyze the purpose of the painting and encourage consideration of improvements.
  "What's this painting trying to express?"
  "What would you do to make it better?"
(3) Diagramming: represent the thoughts on a Systemigram and reflect on them.


Félix Vallotton<The Ball>

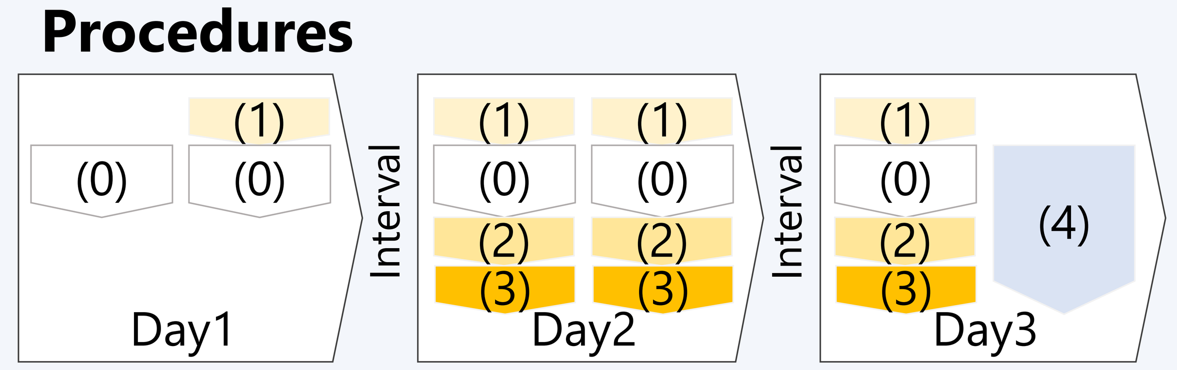


Systemigram drawn by a participant

(4) Application to engineering: apply the processes (0), (2), (3) to the engineering system. Make an observation in their mind, ask five questions, and represent them in a diagram.

Results of the demonstration experiment

Procedures



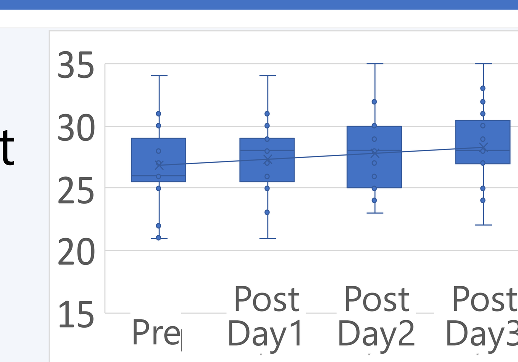
- 3 days step-by-step workshop with two weeks intervals (1.5 hours per day)
- One painting per each VTS (total 5 paintings)
- 4 groups of 5 to 6 people, 21 mid-career engineers from two companies in Japan

Assessment

A) Pre and post-questionnaire (4 times): engagement with systems thinking scale (Camelia and Ferris 2018)
B) Post-questions: asking how they plan to apply them to their future work
C) Pre and post-Systemigrams of a system in charge

Results

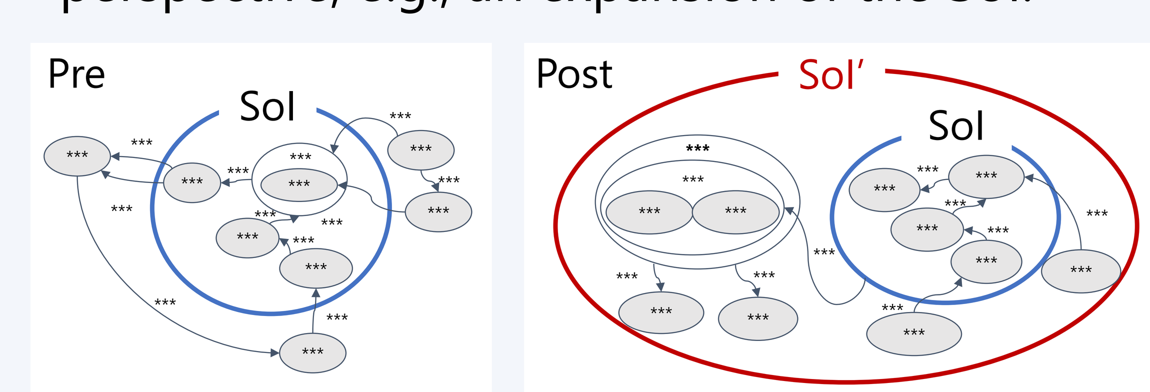
A) A statistically significant increase ($p=0.033$) was found in engagement with systems thinking.



Changes in Engagement Scale

B) Participants proposed expected action ideas, e.g., "I'll consider the impact not only on the responsible module and requested interface but also on related."

C) Systemigrams showed changes in perspective, e.g., an expansion of the SoI.



Pre and Post-Systemigrams of the system in charge drawn by a participant

Conclusions

- We have successfully developed a new method VTS for Systems Thinking based on VTS, which improves engineers' engagement with systems thinking and encourages engineers to use systems thinking.
- The features of the new method are to define painting as a system and that participants observe and analyze paintings using systems thinking, present their thoughts in a systems diagram, and experience an application to an engineering system.
- In the experiment, engineers increased engagement indicates a willingness to participate in system-wide work using systems thinking. Furthermore, the engineers proposed specific and expected action ideas for applying systems thinking to their work. In addition, from the system models drawn, we confirmed that participants expanded their view of the systems in charge.
- The results of this study indicate that we can apply art education methods to systems thinking education.

References

- Yenawine, Philip. 2013. Visual Thinking Strategies: Using Art to Deepen Learning Across School Disciplines. Harvard Education Press.
- Moeller, Mary, Kay Cutler, Dave Fiedler, and Lisa Weier. 2013. "Visual Thinking Strategies = Creative and Critical Thinking." Phi Delta Kappan 95 (3): 56-60.
- Reilly, Jo Marie, Jeffrey Ring, and Linda Duke. 2005. "Visual Thinking Strategies: A New Role for Art in Medical Education." Family Medicine 37 (4): 250–52.
- Camelia, Fanny, and Timothy L. J. Ferris. 2018. "Validation Studies of a Questionnaire Developed to Measure Students' Engagement with Systems Thinking." IEEE Transactions on Systems, Man, and Cybernetics 48 (4): 574–85.

Contact

Akihiro Kitahara
a_kitahara@keio.jp

Integrating System Safety Engineering into STEM Education

Christopher Green

Keywords: STEM education, System Safety, robotics, radio-controlled racing

Abstract

System Safety Engineering is a discipline within Systems Engineering that employs specialized knowledge and skills in applying scientific and engineering principles, criteria, and techniques to identify hazards and eliminate or reduce the associated risks when the hazards cannot be eliminated. This discipline is becoming increasingly important because engineered systems are becoming more complex, which presents safety challenges. Science, Technology, Engineering, and Math (STEM) education has blossomed since the concept was coined by the National Science Foundation (NSF) in the 1990s. Several federally and privately funded initiatives have brought traditional STEM disciplines into middle and elementary school classrooms. Two well-known national initiatives are For Inspiration and Recognition in Science and Technology (FIRST®) Robotics and the TEN80 Education Student Racing Challenge. The emphasis of these initiatives is on traditional engineering fields such as electrical and mechanical engineering. More emphasis should be placed on engineering specialty areas, such as safety, reliability, and security, and how they are integral to the system life cycle process. System Safety Engineering is considered a specialty engineering activity in the INCOSE Systems Engineering Handbook. This paper will present strategies for integrating System Safety Engineering into STEM initiatives and STEM-oriented classroom/ organizational activities.

Introduction

The emergence of STEM in pre-collegiate education within the last twenty-five years has provided a pathway for universities, government, and industry to address the shrinking number of students entering degree programs that will prepare them for STEM careers. Government agencies and industry have earmarked money to form programs and initiatives to address this concern. Several pre-college initiatives, such as Ten80 Racing and FIRST Robotics, are introducing students to the different skill sets they will need to be successful in post-secondary education.

Background

System Safety Engineering

System Safety Engineering is a specialty area of systems engineering with a multidisciplinary approach to designing, developing, and operating complex systems to ensure their safe and reliable performance. Figure 1. shows a general list of the components of system safety. It involves applying engineering and management principles to prevent mishaps or reduce the risk of a mishap to an acceptable level. System Safety Engineering is utilized in aviation, energy, medicine, and the military. It will become increasingly important due to the integration of new technologies, the increased complexity of engineered systems, and the reliance on software to control systems. The incorporation of autonomy and Artificial Intelligence/ Machine Learning (AI/ML) in systems has emerged in the last decade. Some systems are classified as safety-critical because of the way they interact with their environment. A safety-critical system is a system that, if it fails, could result in loss of life, injury, damage to property/ equipment, or environmental damage.

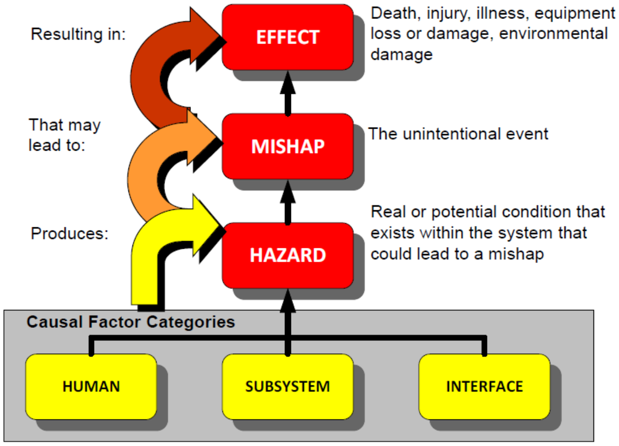


Figure 1. Components of System Safety

There are many processes to do system safety depending on the domain. Below is a system safety process as it applies to military weapon systems:

1. Plan: Plan to get system safety involved in a program as soon as possible
2. Identify: Testing; Data; safety situations, scenarios, failures, and conditions that may uncover, define, characterize, or validate hazards
3. Assess: Assess risk; Various standards available
4. Recommend/ Implement Mitigations: Get buy-in from stakeholders
5. Verify Design and Mitigations

System Safety Engineers and Analysts are the practitioners of System Safety. Some of their key activities include:

- Hazard analysis: Use various methods to identify potential hazards in complex systems, such as fault tree analysis, failure mode and effects analysis, and hazard and operability studies.
- Risk assessment: Assess the likelihood and severity of identified hazards to determine their risk level and prioritize them for mitigation.
- Safety requirements development: Work with teams to develop safety requirements for complex systems, including system design specifications and operating procedures.
- Safety testing and evaluation: Oversee the testing and evaluation of complex systems to ensure that they meet safety requirements and operate safely in various conditions.

- Safety management: Develop and implement safety management plans, which include processes for monitoring and reporting safety issues, conducting safety audits, and managing safety-related documentation.

System Safety Education

System Safety education requires a strong background in engineering or a related field and specialized training in the principles and practices. Continuous learning and professional development are also crucial for staying up-to-date with the latest developments in this field.

To become a System Safety Engineer, you typically need to have a degree in engineering or a related field and specialized training in System Safety Engineering. Many universities offer degree programs in System Safety Engineering or related fields such as Aerospace Engineering or Industrial Engineering. Some universities also offer specialized certificates or continuing education programs in System Safety Engineering for professionals who want to gain additional knowledge and skills in this area. One such program is the University of Southern California System Safety Certificate. These programs may cover topics such as hazard analysis, risk assessment, safety regulations and standards, safety management systems, and human factors engineering.

Professional organizations such as the International System Safety Society (ISSS) offer System Safety Engineers training, certification, and networking opportunities. Obtaining certification from one of these organizations can be beneficial in demonstrating your knowledge and skills in System Safety Engineering to employers and clients.

STEM Education

STEM (Science, Technology, Engineering, and Mathematics) education is an interdisciplinary approach to teaching and learning that integrates these four disciplines. It was first coined by Judith Ramaley, a former director of the National Science Foundation, in the 1990s (3). STEM education focuses on developing students' critical thinking, problem-solving, and analytical skills and preparing them for careers in STEM-related fields.

Many schools and universities offer degree programs, courses, and extracurricular activities in STEM subjects to promote STEM education. These programs are designed to provide students with a strong foundation in math and science and practical skills in areas such as computer programming, data analysis, and engineering. Other activities that promote STEM come in the form of camps, competitions, and clubs that allow students to explore their interests and develop their skills in a hands-on and collaborative environment. Two such programs are FIRST Robotics and Ten80 Racing, which focus on robotics and radio-controlled car racing, respectively.

STEM education is a critical enabler for preparing students for the rapidly evolving job market, where STEM-related skills are in high demand. By providing students with a strong foundation in math and science and practical skills in engineering, technology, and data analysis, STEM education can ensure that students are well-equipped to succeed in the 21st century.

Some Pre-College STEM Initiatives

Ten80 Racing

Ten80 Education is an organization formed in the 1990s. It comprises engineers, scientists, teachers, and professors to help students and teachers understand STEM subjects and how skills learned from them can be applied to everyday life. Ten80 initiates a comprehensive STEM system with the core tenets of Collaboration, Curriculum, and Kick-Offs & Competition in partnership with K-12 schools, organizations, and network partners. The four focus areas of Ten80 Education are Race Engineering, Autonomous Electric Vehicles, Drones, and Computer Science.

The Ten80 Student Racing Challenge is a competition where middle and high school students experience being racing professionals by working as a team to create products using a radio-controlled car. Tasks are structured to mimic a National Association for Stock Car Auto Racing (NASCAR) team preparing for a race, and team members hold positions in engineering, marketing and public relations, project management, driving, and pit crew. Students conduct investigations in three areas of race engineering:

- Problem-Solving through good investigation practices (GIP) and math modeling
- Driving through Data
- Mechanical & Electrical Systems

The racing challenge is the competition tenet. The curriculum for the racing challenge revolves around the following areas:

- Race Engineering Certifications: Problem-Solving through Data & Math Modeling, Driving through Data, Mechanical & Electrical Systems
- Data-Driven Design Projects Include: Aerodynamics, Automotive design, and engineering, Intro to Robotics through Robo Racecar, Energy Challenge applied to racing
- Enterprise & Innovation: Project Management, Business Modeling, Marketing & Public Relations, Graphic Design

The program is designed to teach students about engineering principles, problem-solving skills, and teamwork while also providing opportunities to explore their STEM interests. Students work in teams to design and build their cars, using computer-aided design (CAD) and 3D printing skills to create custom parts. They also learn about electronics and programming as they work on programming their cars' controls and sensors. Throughout the program, students participate in a series of regional and national competitions, where they compete against other teams in various racing events.

In addition to the racing competition, the Ten80 Racing program also includes a range of other educational resources and activities, such as workshops, online courses, and mentorship programs. These resources are designed to support students and educators in developing their STEM skills and preparing for the competition.

FIRST® Robotics Competition (FRC)

FRC was founded in 1989 by Dean Kamen, who is the inventor of the Segway. The FRC program has inspired students to pursue STEM fields since 1992. Kamen's vision was to develop innovative programs to help motivate young people to pursue career and educational opportunities in STEM while providing practical skills to help them succeed.

FIRST® Robotics is a global STEM education program that engages students in robotics and engineering through hands-on, team-based competitions. The program is open to students from elementary to high school and beyond. In FIRST® Robotics, teams of students work together to design, build, and program robots that compete in a series of challenges.

The program includes several different levels of competition, each with its unique challenges and requirements. The FIRST® LEGO League Jr. program introduces students to robotics and engineering concepts using LEGO bricks and simple robotics kits at the elementary school level. At the middle school level, the FIRST® Tech Challenge program challenges students to design and build robots to complete complex tasks, such as navigating obstacles and picking up objects. At the high school level, the FIRST® Robotics Competition (FRC) is the flagship program of FIRST Robotics. In FRC, teams of students design and build large-scale robots that compete in complex challenges that change each year. The competition is designed to simulate the experience of a real-world engineering project, with teams working together to solve problems, design solutions, and meet deadlines. In addition to the robotics competitions, FIRST® Robotics also offers a range of educational resources and activities, including online courses, mentorship programs, and outreach programs designed to promote STEM education in underserved communities.

Overall, FIRST® Robotics is an innovative and engaging program that provides students with a unique opportunity to learn about engineering, robotics, and teamwork in a fun and supportive environment. The program has inspired thousands of students worldwide to pursue careers in STEM fields and has helped build a global community of innovators and problem-solvers. The combined impact projected for all FIRST® programs for the 2022-2023 season is 38,700 teams worldwide, with 400,000+ students participating in various events and $20 million in college scholarships. The 2023 FIRST® Championship was held in Houston, TX.

Integrating System Safety

This section describes how STEM activities can be integrated into Ten80 Racing, First Robotics, and as organizational/ classroom outreach.

Ten80 Racing

The Ten80 System Safety Challenge is an activity that could be added to the existing Ten80 racing program.

Ten80 System Safety Challenge: The Ten80 Racing competitions and challenges are well documented in their handbook. The system safety challenge would be an additional activity that could be incorporated within the existing competition or used as a separate stand-alone competition. The proposed system safety challenge would include an introduction to system safety that will cover topics such as:

- What is System Safety, and Why is it Important?
- Hazard Analysis
- Risk Management

The main activity will be the addition of a passenger in the form of an egg in the car's chassis. The goal is to develop a system that allows the egg to remain intact when subjected to different impact events. Participants will design a method to keep the egg from breaking during a five-lap run on an oval track as defined by the oval track race requirements. Data-Driven Design will determine the circumstances under which the egg would break. A safety standard such as MIL-STD 882E would then be used to perform a safety analysis on the car relative to the egg. The participants will then design and implement safety engineering controls to keep the egg from breaking in due to a mishap. The following deliverables will be required of all participating teams.

- Documentation: Teams submit documentation (including safety analysis) of their safety engineering controls and safety assessment through the competition website
- Visual presentation: Teams are given a table to display their projects.
- Judges Interview: Teams spend 10 minutes with judges at their display area.

Submissions will be graded using a rubric. Deliverables will be uploaded to the competition website.

FRC

FRC teams compete with a complex robot defined by a Concept of Operations (CONOPs), a set of requirements, rules, and a competition kit containing parts, equipment, and software. FRC competitions in past years have engaged robots to play basketball, ultimate Frisbee, soccer, and various other games. As can be imagined, there are many hazards in constructing a 100+ pound robot engaged in a competition. The robot system may include moving parts, pneumatics, electricity, and hazardous materials. FRC has adopted safety as a core value and established the framework for safety leadership in all aspects of the program and throughout the competition season.

The emphasis on safety within FRC culture can be leveraged for education on how safety analysis is performed in the context of system safety. This could be accomplished with a hazard brainstorming activity.

Hazard Brainstorming: FRC promulgates an extensive safety program. A safety manual is provided to all teams, with safety considerations additionally incorporated throughout all competition documents. It gives safety procedures on Personal Protective Equipment (PPE), tool usage, energy, human systems integration, and facility safety. The documentation would lend itself to creating a Preliminary Hazard List (PHL) and then a Preliminary Hazard Analysis (PHA), two analysis tasks described in MIL-STD-882E. Participant teams would be provided documentation on writing a hazard and provided a copy of the FRC Safety Manual. Teams would then brainstorm and document hazards, causal factors, and effects. Teams are encouraged to use their critical thinking and expand beyond what is in the safety manual.

Additionally, teams are recognized for their contributions to safety. Awards are presented to teams that excel in safety concepts at FRC events. An Industrial Safety Award is sponsored by Underwriters Laboratories (UL) that celebrates the team that progresses beyond safety fundamentals by using innovative ways to eliminate or protect against hazards.

General

System Safety Engineering can also be incorporated into STEM fairs and outreach events. The Systems Safety Engineering Division of Naval Surface Warfare Center Dahlgren Division has held several successful activities to expose youth from the local community to system safety practitioners' work and tasks. During one activity shown in Figure 2, the children competed in balloon rocket races by racing balloons across a zip line. Before the activity, the children were engaged in a discussion on developing and identifying safety hazards. This is then extended to the activity where the hazards of the rocket races were discussed, such as a fall hazard while placing the balloon on the zip line, personnel injury from a cut or abrasion while clipping their balloon to the zip line, and similar.

Figure 2: Balloon Rocket Races

In another outreach activity, children rotated through various stations relating to system safety. At one station, the children were informed about PPE and how it minimizes personnel exposure to workplace injuries and illnesses. For the activity, the children had to dress their 'paper cutout doll' in the correct PPE for the scenario. A sample scenario was that they were spray painting parts in a workshop. What PPE should they wear? The students should then place a respirator, safety goggles, coveralls, and gloves on their cutout doll. Another station included the MIL-STD-882E mishap risk table of severity and probability shown in Figure 3. The students were challenged to target the appropriate risk level using a toy bow and arrow. The green 'Low' risk levels are on the matrix for the highest point score. Hitting a 'green' Low-risk level box would trigger a higher point value than hitting the neighboring High (red), Serious (orange), or Medium (yellow) risk levels. The activity correlates to activities we perform as system safety engineers to lower hazard severities and probabilities or to design them out. At another station, the participants could let their creative juices flow to create safety warning signs to take home. A variety of basic sign shapes, as well as safety icons, were provided for the activity.

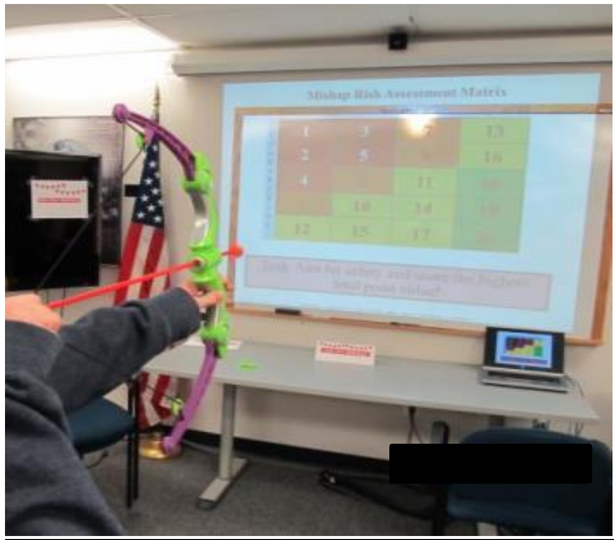


Figure 3: Aim for Safety

Conclusion

System safety is a specialty engineering area that manages risk using a systems approach. The need for system safety will grow as engineered systems become more and more complex. System safety is taught in a limited scope at a few universities, making it relatively unknown compared to traditional engineering areas.

There is a shortage of scientists and engineers in the United States, and STEM was created to identify and target that shortage. Since its inception, STEM has targeted traditional engineering disciplines. More attention needs to be given to systems engineering and specialty engineering areas as career paths. This paper shows how system safety can be integrated into traditional STEM initiatives such as First Robotics, Ten80 Racing, and organizational classroom events.

References

1. Department of Defense (2012). *MIL-STD-882E, Department of Defense Standard Practice System Safety*, 11 May 2012.
2. Ericson, C.. (2005). *Hazard Analysis Techniques for System Safety*. John Wiley & Sons. Inc.

3. FIRST Robotics Competition (FRC) Web Site. (Accessed 1 July 2023). www.usfirst.org
4. Green, C., Owens, T., and Scarabello, N., (2015). *Strategies for Infusing System Safety Engineering into Pre-College Science, Technology, Engineering, and Math (STEM) Initiatives*. Proceedings of the 33rd International System Safety Conference. San Diego, California. August 24-27, 2015.
5. Koonce, D., Zhou, J., Anderson, C.. (2011). *AC 2011-289: What is STEM?* American Society for Engineering Education.
6. Ten80 Education Web Site. (Accessed 1 July 2023). http://www.ten80education.com/
7. Ten80 Racing-National STEM League-Ten80 2014-2015 Education Handbook.
8. Zemore, Mike and Boscovitch, Etienne. (2009).“*Training the System Safety Engineer*."Leading Edge (System Safety Engineering) Vol. 7, Issue No. 3. Naval Surface Warfare Center, Dahlgren Division.

Biography

Christopher Green is originally from Newport News, Virginia, and served 8 years in the U.S. Army. He attended college on the GI Bill and received a B.A. in Applied Physics from Christopher Newport University. Mr. Green then taught high school physics for Richmond City Public Schools in Richmond, Virginia. He then worked at Virginia Commonwealth University School of Engineering for nine years. There he earned an M.Ed. in Adult Education and an M.S. in Mechanical Engineering. Mr. Green has worked as a systems engineer on weapons systems for the U.S. Navy for the past 15 years. He has a Certificate in System Safety from the University of Southern California and is an INCOSE Certified Systems Engineering Professional (CSEP).

Shu Ha Ri for SE; The Paper

Previously available in:
Proceedings of the IISE Annual Conference & Expo 2023
K. Babski-Reeves, B. Eksioglu, D. Hampton, eds.

Fred Y. Robinson
Systems Engineering Innovation Center, The MITRE Corporation, McLean, VA, 22102, USA

Abstract

This presentation offers a perspective for considering enhancements to the current programs for developing systems engineering professionals, incorporating consideration for developing characteristics of expertise and mastery throughout, summarizing my previously published paper. Shu Ha Ri represents an approach for three phases of mastery development, established in ancient practices such as martial arts and mimicked in current approaches. Ericsson's research on expertise depicts three levels of progression, naïve practice > purposeful practice > deliberate practice. However, Eriksson's model is limited to domains where the demonstration of expertise can be characterized, is well understood, and is measurable or at least objectively evaluable by existing domain experts. Yet, for a given population of experts in systems engineering, there is a shared thematic set of highly diverse experiential assessment characteristics which diverge from some of the earlier assessment levels. Epstein suggests the power of generalists comes to play more when experts address wicked problems (those lacking a pre-ordained approach for solving) than when specialists address kind problems (the opposite). Kind problems are not necessarily easy to solve, but the route is well defined. Solving wicked problems without exemplar solutions often requires the generalist's leveraging of analogic thinking, and the recognition and possible synthesis of matchable patterns (e.g., isomorphisms) learned from diverse experience sampling of other domains, not merely relying on T-shaped or Pi-shaped knowledge. Using the Shu Ha Ri framing presents an opportunity to consider enhancements to earlier systems engineering practitioner development stages towards excelling beyond emergence and effectiveness.

Keywords: Shu Ha Ri, expertise, generalist, specialist, systems engineering

1. Introduction

Serendipity – having good things happen just by chance or luck – can be fickle, whether it influences an instant in one's life and career such as a single interaction, or if one's entire life and career is perhaps defined by the summation of a string of serendipitous events. Then again, in spite of mere coincidence, it would seem still possible to influence conditions that might encourage preferential outcomes for one's life or career, leaving in question whether chance or planning had the greatest impact. Instead of *high-stakes* experiments, such as swapping circumstances for the characters Billy Ray Valentine (Eddie Murphy) and Louis Winthorp III (Dan Ackroyd) to test whether circumstances of *nurture or nature* has greater impact on success such as in 1983's classic movie Trading Places, what if there were somewhat more general recommendations to follow where they both could achieve success without everyone having to follow the same singular path? Why would we rely solely on serendipity for shaping our professional careers?

Oddly enough, one serendipitous event occurred for me in late 2021, as I happened to see a Call For Papers for the Insight journal published quarterly by the International Council of Systems Engineering (INCOSE), for an announced themed issue focusing on the "The Unique Abilities of the Systems Engineer" [1]. As chance had it, I had been piecing together a mental model to share what I saw regarding skill and knowledge development stages in our discipline, building upon my readings in a multitude of books and articles, and now I had a potential venue with a corresponding set of topical constraints to shape and share my thoughts.

Many consider the discipline of systems engineering to be akin to any other highly specialized field, where there's a standard body of knowledge to be mastered and its highly skilled practitioners fit a narrowly shaped (yet difficult to achieve) definition of being an *expert*. My own observations place systems engineering in a different reality. Over the decades of our field's existence, the introduction of many extensions and a multitude of sub-specializations are simultaneously encouraging growth and innovations while also engendering divisive debates and disagreements about

Approved for Public Release; Distribution Unlimited. Public Release Case Number 23-0261.
© 2023 The MITRE Corporation. ALL RIGHTS RESERVED.

what actually constitutes an *expert* systems engineer. Constructs from four literature works, when pieced together, have helped me to put form to my mental model extending where systems engineering fits traditional specialization expertise yet also demands novel considerations for how and when we start shaping our field's future experts.

My four recommended (semi-requisite) readings are:

- Peak: Secrets from the new science of expertise, (book) by Anders Ericsson [2]
- Range: Why generalists triumph in a specialized world, (book) by David Epstein [3]
- Development of systems engineering expertise, (journal article) by James Armstrong & Jon Wade [4]
- The meaning of Shu Ha Ri, (web page) by Dan Dease [5] as an example, and others

With these four works in mind, I realized the BLUF (i.e., bottom line up front) is: **If we make the mistake in thinking that "the path" towards *expert level mastery* for systems engineers is just like any other specialization…Then, those who seek to approach such mastery may only succeed through *serendipity*.**

My prior published paper, *For the Journey to Expertise in Systems Engineering, Enhance the Path with Shu Ha Ri*, [6], provided the impetus for my IISE 2023 Annual Conference presentation as well as foundation discussion for how Shu Ha Ri serves as frame for systems engineering expertise development. This IISE conference paper details and extends the messages shared in the IISE presentation which itself explicates the prior INCOSE Insight paper, including some additional discussion for future opportunities and reflections beyond the constraints of the earlier work.

2. Problem Description and Background

Like many other evolving disciplines, systems engineering elders have endeavored to create an epistemology for identifying the knowledge to share with the upcoming generations of practitioners and a corresponding pedagogy for delivering the desired outcomes. INCOSE in particular has worked on some excellent exemplars, including their Systems Engineering Handbook [7] detailing foundational knowledge typically focused on the emergent practitioners, and INCOSE's Systems Engineering Competency Framework [8] containing over 30 competencies, each with their specific level definitions of mastery, supporting development of effective practitioners. Yet, when I was doing a literature review homework related to an early doctoral research topic, I came across the above referenced grounded theory study by Drs. Armstrong and Wade. Looking at the thematic-extracted experts' characteristics from their study of INCOSE Expert Systems Engineering Professional (ESEP) and other recognized disciplinary experts, only a few aspects reflected an extended refinement of skills aligned to the INCOSE' competency and foundational knowledge models, as would be suggested by Ericsson's expertise definitions in his book Peak. Around this time, a peer suggested I also read the book Range by Epstein. I started to see a problem with the discontinuity in going from effective to expert practitioner, one that the varietal knowledge acquisition of generalist seemed a viable candidate as a bridge.

One more event of serendipity was my discovering a mention of an ancient construct in an expertise-focused article. Further exploration exposed that **Shu Ha Ri** is an approach for three phases of mastery development, simply translated **Shu** for learning the basics ("follow" – to know), **Ha** for learning tools ("seek" – to do), then **Ri** for extending beyond just tool usage or skills execution ("leave" – to excel) [6]. Like many Eastern philosophical constructs, Shu Ha Ri has been occasionally reconstituted to be more in line with Western positivism, thought its roots are described as coming from 15th century sword-making mastery development. The agile development community makes claims to follow Shu Ha Ri, focused mostly on just one trip of progressing through the mastery levels. There are Aikido martial arts trainers who present Shu Ha Ri for mastery development with the Eastern view towards continual, iterative, diverse paths of amassing skills, yet other trainers can be found that do not. The competition television series Forged in Fire on the History Channel depicts metalsmiths early in their mastery development being given novel challenges to test their craftsmanship, most importantly followed by critical feedback toward improvement. I started to see the emerging parallels to all these different mastery development paths as well as some gaps, such as the lack of one-on-one skills development between the learner and the teacher. I still believed there was an opportunity to find and represent the synergy of the four areas of thought I had observed from Ericsson, Epstein, Dease, and Armstrong and Wade, which could describe the uniqueness of the journey toward expertise in systems engineering, which in turn could then better inform how we as a practice can guide future expertise development without having to rely so much on serendipity to intervene.

During my years at Lockheed Martin (LM) as a systems engineer and later as a system architect, I perceived a corporate culture where the systems architect was a defined profession for staff [9] that could be seen somewhat as an

Approved for Public Release; Distribution Unlimited. Public Release Case Number 23-0261.
© 2023 The MITRE Corporation. ALL RIGHTS RESERVED.

über systems engineer. In my first year at LM, I was lucky to have a senior manager recommend that I pursue the internal certification as an LM Systems Architect. Using their internal process-based assessment, I was able to work with my sequence of managers to gain necessary and broad experience through assignments from pre-acquisition through to sustainment of deployed solutions and systems, to develop and design systems, to envision and define solution architecture, to work across / with diverse types of stakeholders, technologies, and lifecycles. When I left LM, I found myself in a very different corporate culture, one where architecture was just one skill that an *über* systems engineer should possess. This dichotomy showed me that there was not a single definition for expertise in our area of practice. With a greater involvement with INCOSE, I started to look at their ESEP evaluation process to consider any similarities and differences to LM's expertise recognition program. Beyond the lack of consistent taxonomies of skills or competencies and the variable assessment criteria and methodologies, the one clear similarity was that expertise in others could only be validated by IKIWISI [10], or "I know it when I see it," subjective assessments by representatives of the current cadre of local disciplinary experts. Even in context of the INCOSE Competency Framework and its peers, it would seem that measures or tests of explicit knowledge poorly approximate actual expertise, which instead is consigned to predominately subjective assessments.

In a prior work, I suggested four aphorisms for effective systems engineers, including one that is "we are generalists" [11] many months before Range was released, with its own description of what makes generalists special. One problem is overcoming some perceptions that a generalist would have consistently limited depth in favor of significant breadth, that they'd be *a mile wide yet an inch deep* in their skills or "dash" (-) shaped, whereas systems engineering's generalists are characterized more so by "Pi" (π) shaped or even "comb" shaped professionals with significant breadth and multiple depths [12]. Western philosophy's positivism tends to shape paths to expertise with linear thinking and uni-directional thresholds, where the beginner's transition to an intermediate level as well as the intermediate to advanced transition typically involve never returning to the learning types experienced at the prior mastery levels. How then can systems engineering generalists flourish when our Western mentality push them towards increasingly narrowed specializations of mastery? Systems engineering experts often must leverage their tacit knowledge gained through a career of sampling challenge areas, to enable addressing the most novel meta-disciplinary problems.

Range also frames the importance in value of generalists versus specialists as exposed in the difference between what Epstein refers to as "wicked" problem solving versus "kind" problem solving. In Range, *kind problems* are not necessarily easily solved, but the solution approaches are well defined, whereas *wicked problems* are best identified by the lack of an approach pre-ordained by past experts for getting to a solution. While Epstein seems to mistakenly transmute an analysis by Hogarth, et al., of the impact of *learning environments* of being *wicked* or *kind* (e.g., where kind environments encourage learning and wicked environments hamper learning) [13] morphing the dichotomy to be about a *challenge* itself being *wicked* or *kind* in his book's first chapter, his remaining observations that identify where the generalists are typically the most effective at addressing wicked problems is a powerful consideration. While there are many kind problems that can be addressed by effective practitioners of systems engineering's defined methods, experience suggests that the most pernicious challenges we encounter benefit most from the assignment of our disciplines experts who most demonstrate the power of the generalist's mindset. Consider one well-known wicked problem of the early 1900's that we now consider kind, which was the initial challenge of sustained, powered, manned flight that is repeatable, survivable, and controlled, as a full scale, heavier than air vehicle [14], or as we kindly and more briefly call it, "flight."

My challenge remained how to integrate the strengths and unique intersections of the four works into a descriptive representation that could easily resonate for systems engineers across the breadth of experience/mastery levels and from various disciplinary segmentations. My desired outcome is that a more unified model could be used to inform any multitude of journeys and paths one might take toward mastery without just having to hope that serendipity's influence will guide them towards their desired outcome.

3. Discussion

Another common aphorism that has persisted, *hindsight is 20/20*, which when said otherwise, suggests that looking backward is easy and always seems clear. When I was still at LM near the end of the first decade of the millennium, an internal corporate exchange conference was held by and for their LM Fellows, LM's highest technical distinction. I was able to watch the recording of one panel session where the moderator asked the empaneled staff about their paths to becoming an LM Fellow. Listening to the first few Fellows share how they could look back at how their positions held, learning exposures, and choices made enabled their respective success, it was clear that there was no

Approved for Public Release; Distribution Unlimited. Public Release Case Number 23-0261.
© 2023 The MITRE Corporation. ALL RIGHTS RESERVED.

single or even similar path. Then one LM Fellow summed up his own experience (as well as his peers' experiences) with one statement, "I guess it is that I survived the shark tank!" Serendipity seemed to have struck again.

Ericsson's research on expertise has highlighted several critical considerations relevant for systems engineers. Not only does the achievement of expertise take a significant commitment of time, the ways in which humans learn and hone skills must change depending upon which level of attainment pursuit is in progress. Figure 1, part (a), visualizes Ericsson's model as it maps to other sequences of mastery acquisition in practices and even academia. For example, learning the basics of tennis (or foundational concepts of systems engineering) in Ericsson's *naïve practice* stage enables performative playing (or execution), yet just continuing to perform based upon such basic skills for and extended time, like for 10,000 hours, only guarantees exhaustion and not expertise development. Changing to a new learning and skill development paradigm as an inflection point beyond foundational competencies enables a new trajectory that Ericsson calls *purposeful practice*, as a phase to begin to learn and eventually master the techniques and tools to continue to improve one's performance. Attainment increases are incremental, and they require getting out of one's comfort zone, along with significant passion to keep improving and to break through plateaus at inflection points for changing the paradigm of skill development.

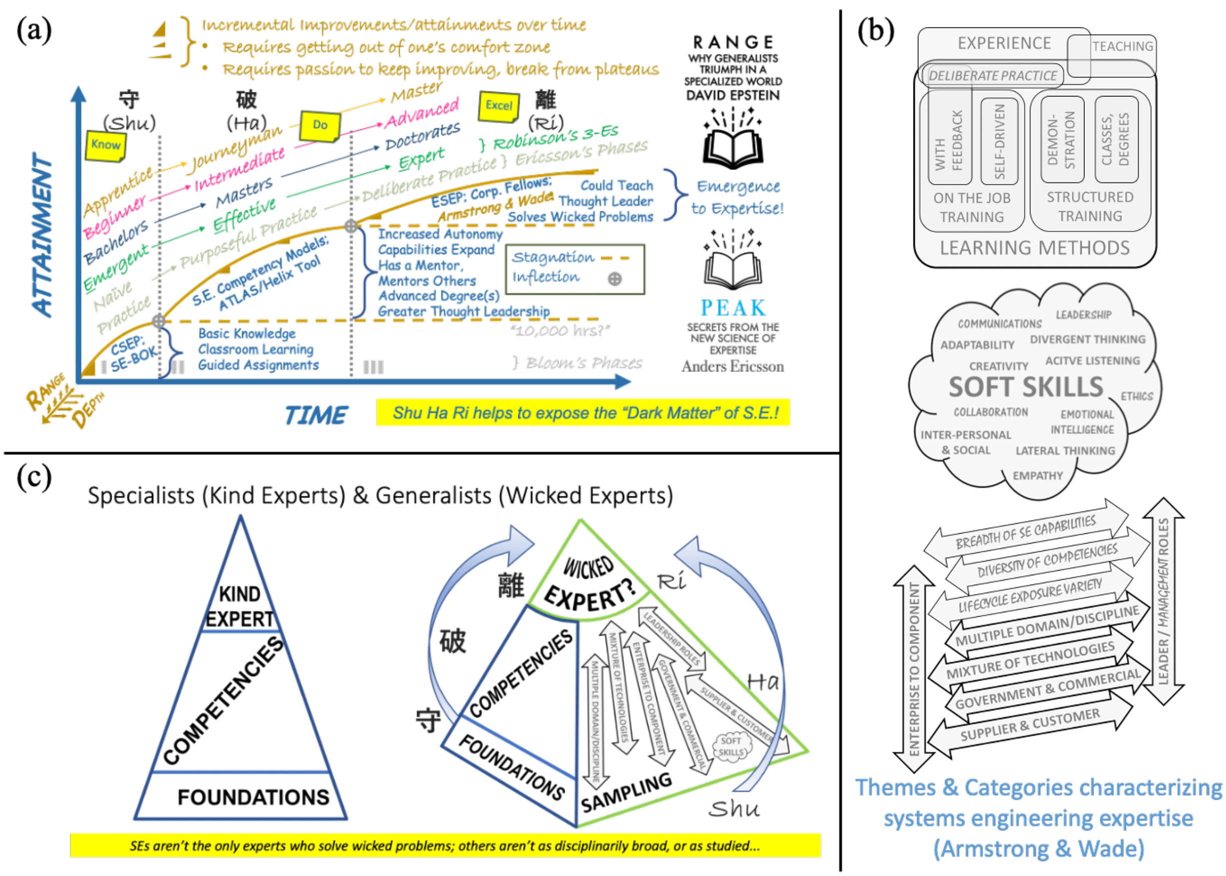


Figure 1: Visualizations supporting Shu Ha Ri for S.E. **(a)** mapping between Shu Ha Ri, systems engineering knowledge, via Peak's skills evolution and Range's depth, **(b)** mapping the themes and categories in Armstrong & Wade, **(c)** depicting Peak's basic expertise the with dimensionality of Range's sampling, enabled by Shu Ha Ri.

INCOSE's Systems Engineering Competency Framework has over 30 defined areas to master through multiple defined levels of attainment for each individual competency, the set of which seem to correlate well to Ericsson's purposeful practice. However, invoking the systems maxim of the *whole is greater than the sum of its parts*, can systems engineering expertise merely be measured by the attainment individual mastery 30 plus competencies? Framing systems engineering expertise by Armstrong & Wade's grounded theory research as visualized in Figure 1, part (b), suggests that indeed there is more to be considered beyond a diverse set of competencies, which is also built upon the shared learning methods and soft skills found in our experts. Ericsson's third stage of attainment, *deliberate*

Approved for Public Release; Distribution Unlimited. Public Release Case Number 23-0261.
© 2023 The MITRE Corporation. ALL RIGHTS RESERVED.

practice, is where specialized expertise would be honed, but systems engineering's experts seem to reflect different characteristics of performance than just extreme mastery of a constrained set of well-defined skills or competencies, rather it is an emergence to expertise – but why?

Epstein in Range describes the generalist, among other aspects, as having experienced significant sampling and variety in experiences upon which inherent skills are built. This sampling allows for any practitioner to imprint with a multitude of isomorphisms (e.g., solution agnostic patterns of systems behaviors). Isomorphisms become transferrable to new problem frames by generalists who also leverage their aptitude as allegorical thinkers. Isomorphisms also can be synthesized together to form novel approaches to the most wicked problems, leveraging generalists' propensity as divergent thinkers and critical thinkers. These types of synthesis fit Dan Ward's most basic definition of innovation, *novelty with impact* [15], a trait associated with disciplinary experts as *thought leaders*, or literally as *thinking leaders*.

Armstrong & Wade identified numerous spectra across which sampling, such as Epstein describes in Range, have occurred in the careers of their research participants who have already achieved recognition of their expertise as depicted in Figure 1, part (b), in the bottom third of the graphic. Beyond the spans of capabilities, competencies, and lifecycle variety, where do the emergent to effective practitioners get advised toward opportunities that span from components up through enterprises, additional domains/disciplines, unexplored technologies, governmental vs. commercial, and across different supply chain stages? The influence of such sampling across the identified spectra however is not reflected in systems engineering's developmental tenets of learning foundational knowledge and developing skills within a set of competencies. This gap of omission, or perhaps the commission of exclusion, could be closed once these attributes are recognized as a valuable addition to the pedagogy for development of systems engineering expertise. Currently, our senior-most peers are left to point at the *hindsight* of those who have already achieved expertise through sampling and then ask those in the next generation, why didn't you do that too?

This is where Shu Ha Ri comes in! Beyond the synergistic parallels of having three stages, which I more simply represent as "to do," "to know," and "to excel," which fit nicely against Ericsson's three phases of practice, Shu Ha Ri in its Eastern philosophical incarnation is premised on being acceptable to be at different stages across multiple (e.g., a sampling) learning paths concurrently. Westerners recoil from the idea that after crossing the threshold to intermediate performance, that returning to having a beginner status is a regression rather than an opportunity for growth, and as well after the transitioning a threshold to advanced performance. Fundamentally, Shu Ha Ri done right encourages the generalist's sampling described in Epstein's Range. Systems engineering's pedagogy needs to be enhanced to reinforce the benefits that can be achieved from planning for sampling, versus hoping for serendipity. As depicted in Figure 1, part (c), reshaping how we develop the future generation by adding the sampling discussed should then encourage develop wicked-experts, instead of just kind-experts.

Secondly, the training philosophy of Shu Ha Ri focuses on the relationship between the learner and the trainer (or teacher), akin to the tradesmen who apprentice first under a master-craftsman, then serve in journeyman roles still under the guidance of their trainer, with significant shared commitment on both sides of the relationship. Modern disciplines have come to leverage what are thought to be more efficient methods such as computer-based training, recorded classes, and greater reliance on testing only knowledge that can be evaluated via automata, diminishing the ability for a human connection to learning. Additional modern efficiencies seem to come from promoting *mentoring* and *job-shadowing* programs, which while they can be both informative and possibly even entertaining, such programs are no substitute for apprentice/journeyman focused style of training with an expert teacher. Modern systems engineering's continued pursuit of digital engineering leveraging model-based applications, with their many benefits to productivity, unfortunately results in the primary relationship of an emergent learner being with their computer's human interface devices rather than with another more experienced human. Ericsson's research emphasizes that it's both the type and quality of constructive feedback, including positive and negative feedback opportunities, to be effective at attaining greater levels of performance, and such feedback is not well integrated into our modern technology-centric engineering performance platforms.

4. Conclusions

There are many benefits that can be gained for most disciplines by following a particular approach to training and development. Systems Engineering is somewhat distinguished from others as many of its expert practitioners do not typically fit the model of merely being kind problem solvers, rather our experts often provide the most innovative solutions to wicked interdisciplinary or even transdisciplinary problem spaces. Recognizing the discipline's experts by relying on whose path best relied on serendipity is an ineffective model. Sampling and other generalists'

Approved for Public Release; Distribution Unlimited. Public Release Case Number 23-0261.
© 2023 The MITRE Corporation. ALL RIGHTS RESERVED.

experiences appear to demonstrate value of and encourage attainment of systems engineering expertise more rapidly and effectively than traditional linear approaches. Framing new approaches to learning and development in Shu Ha Ri enables a focus on encouraging these important elements for future generations of systems engineering practitioners.

This is not to suggest that systems engineers represent the only experts who solve wicked problems. The challenge is that other areas of practice may not be as disciplinarily broad, or as well studied as is systems engineering, to expose the advantages and pathways to leverage the power of generalists along with their particular expertise.

Acknowledgements

The author's affiliation with The MITRE Corporation is provided for identification purposes only, and is not intended to convey or imply MITRE's concurrence with, or support for, the positions, opinions, or viewpoints expressed by the author. ©2023 The MITRE Corporation. ALL RIGHTS RESERVED.

Approved for Public Release; Distribution Unlimited. Public Release Case Number 23-0261.

References

[1] INCOSE, "Call for papers: The unique abilities of the systems engineer." Dec. 15, 2021. [Online]. Available: https://www.incose.org/events-and-news/incose-and-se-news/2021/12/15/call-for-articles-incose-insight-september-2022-theme-the-unique-abilities-of-the-systems-engineer
[2] K. A. Ericsson, *Peak: Secrets from the new science of expertise*. New York: Houghton Mifflin Harcourt, 2017.
[3] D. Epstein, *Range: Why generalists triumph in a specialized world*. New York: Riverhead Books, 2021.
[4] J. R. Armstrong and J. Wade, "Development of systems engineering expertise," *PROCS Procedia Comput. Sci.*, vol. 44, pp. 689–698, 2015.
[5] D. Dease, "The meaning of Shu Ha Ri," Jun. 29, 2010. http://www.kimusubiaikido.com/blog/meaning-shu-ha-ri (accessed Dec. 27, 2021).
[6] F. Y. Robinson, "For the Journey to Expertise in Systems Engineering, Enhance the Path with Shu Ha Ri," *INSIGHT*, vol. 25, no. 3, Art. no. 3, Sep. 2022, doi: 10.1002/inst.12397.
[7] INCOSE, *Systems engineering handbook: A guide for system life cycle processes and activities*, Fourth. San Diego: INCOSE, 2015.
[8] R. Beasley, D. Gelosh, M. Heisey, I. Presland, and L. Zipes, "INCOSE Systems Engineering Competency Framework, Version 1.0," INCOSE, San Diego, INCOSE-TP-2018-002-01.0, 2018.
[9] J. Poulin, "LM ADQP: Development & qualification program for architects and technical leaders," presented at the SEI SATURN conference, St. Petersburg, FL, May 09, 2012. Accessed: Oct. 31, 2015. [Online]. Available: http://www.sei.cmu.edu/library/assets/presentations/poulin-saturn2012.pdf
[10] B. Boehm, "Requirements that handle IKIWISI, COTS, and rapid change," *Computer*, vol. 33, no. 7, Art. no. 7, 2000.
[11] F. Y. Robinson, "Exploring the core of systems engineering." SSRN, 2019. [Online]. Available: https://ssrn.com/abstract=3339087
[12] I. K. Trogstad, S. Kokkula, and J. van der Aker, "Application of T-shaped engineering skills in complex multidisciplinary projects," in *31st Annual INCOSE International Symposium Proceedings*, Virtual, Online, 2021.
[13] R. M. Hogarth, T. Lejarraga, and E. Soyer, "The two settings of kind and wicked learning environments," *Curr. Dir. Psychol. Sci.*, vol. 24, no. 5, pp. 379–385, 2015.
[14] D. Ward, *Lift; Innovation lessons from flying machines that almost worked and the people who nearly flew them*. Lulu, 2019.
[15] D. Ward, A. Khaw, J. Choi, L. Cuppernull, K. Thompson, and G. Raymond, "ITK-Handbook." MITRE, 2022. Accessed: Jan. 23, 2023. [Online]. Available: https://itk.mitre.org/wp-content/uploads/2022/06/ITK-Handbook.pdf

Approved for Public Release; Distribution Unlimited. Public Release Case Number 23-0261.
© 2023 The MITRE Corporation. ALL RIGHTS RESERVED.

Human Systems Integration: From STEM[1] to STEAM[2]

Dr. Guy André Boy, INCOSE Fellow
FlexTech Chair Director and University Professor
Paris Saclay University (CentraleSupélec) and ESTIA Institute of Technology

Setting the scene

The shift from Industry 4.0 to Society 5.0 in the evolution of contemporary systems engineering requires including people and organizations within the whole life cycle of sociotechnical systems. This endeavor starts from an early age and is further developed at school. Consequently, education and training must include human systems integration (HSI) as a discipline at the same level as mathematics and physics (Boy, 2023). We have started this experience within the FlexTech Chair, a research and education program supported by Paris Saclay University (CentraleSupélec) and ESTIA Institute of Technology. HSI is based on digital engineering providing tools that enable students to learn by doing through the creation, testing, and refinement of virtual prototypes of any kind. Human-in-the-loop simulation (HITLS) capabilities allow the observation and discovery of emerging properties of sociotechnical systems being designed. At the same time, we develop creativity, participatory methods, and tangibility criteria to assess various types of maturity (technological, human, and organizational).

By using HSI transdisciplinary approach, students can learn to connect underlying disciplines and collaborate with other students to achieve something greater than they could alone. This paper presents practical HSI concepts illustrated by examples of educational HSI experience. The first use case concerns creating a new healthcare system where general practitioners (GPs) are the main actors. GPs know their patients and can communicate appropriately with specialists and hospitals. This project is called INNOMED. Over the past three years, this project has been entrusted to engineering, human factors, and business students (22), who have generated significant proposals and possible solutions. However, learning about creativity, systems thinking, collaboration, negotiation, and sharing authority was the best outcome. Another group of aerospace and business students (10) developed a second use case for making a space habitat on the Moon. Students had to switch between a creative mindset and managing well-established knowledge in space mechanics and geology. They learned physics by creating artifacts, testing their innovative hypotheses, and verification by subject matter experts (learning by doing). In summary, a pedagogical process under development mixing creativity and hard sciences is presented and discussed.

Is the "experienced creativity" statement an oxymoron?

We could not go to the Moon without a big deal of two assets: **experience** and **creativity**. They can be contradictory concepts. Experience results from appropriating, accumulating, and integrating many facts, episodes, failures, and successes. Experience is made of cumulative and integrative practice, knowledge, and know-how. It is typically conservative and leads to "educated common sense!" Conversely, at the same time as being a process, creativity is a state of mind that pushes us to "get out of the box." It is often the opposite of what our educated

[1] Science, Technology, Engineering, and Mathematics.
[2] Science, Technology, Engineering, Arts, and Mathematics.

common sense tells us to do. Creativity is based on exploration, risk-taking, try-and-error processes, imagination, anticipation, etc. Innovation is about combining creativity and experience. Why? If we want to build something sustainable, it is essential to make sure what we produce is tangible. Tangibility has two sides: physical and figurative (Boy, 2023).

Physical tangibility is a property of a phenomenon consisting in grabbing physical things (e.g., holding a glass is tangible). **Figurative tangibility** is about grabbing ideas, concepts, or abstractions (e.g., if you clearly understand what I am saying, you could tell me, "This is tangible!"). This is why these two facets of tangibility must be taught. In our INNOMED project, students had to be creative, using their imagination, dreams, and projections to generate potential solutions. They also had to explore the healthcare field through interviews with GPs and other healthcare stakeholders who provided pieces of their experience. The results were compelling.

In developing the space habitat on the Moon, the other students had the same creativity and use of space domain experience that included operational experience and complex science knowledge – they were lucky to have two former NASA professionals, an engineer and a space explorer (Boy, Doule, Kiss & Mehta, 2018; Boy, 2019). They also used the results of an ISU[3] project (Aarrestad et al., 2012; Boy, 2012). For example, they had creativity sessions where they imagined and defined various kinds of concepts of operations (ConOps) based on available professionals' experience and evaluation (Figure 1).

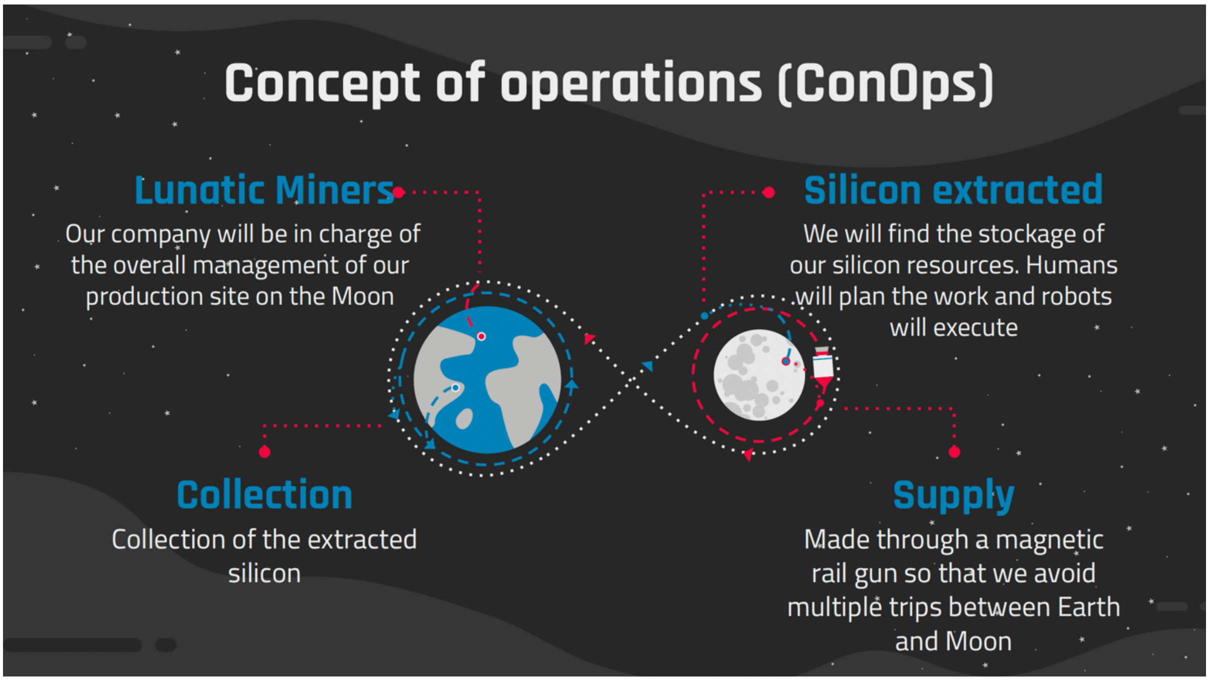


Figure 1. An example of student production (the topic was silicon extraction on the Moon).

Procedure following, automation, and problem-solving.

For a long time, mastering life-critical complex systems, such as flying a commercial airplane or controlling a nuclear power plant, required following **operations procedures** and monitoring automated systems. Operations procedures tend to automate people. Machine

[3] International Space University.

automation results from implementing procedures into software. These two types of **automation** led to rigidifying operations within well-defined operations contexts, that is, in expected situations. However, when unexpected problems occur, more profound knowledge and know-how are required to keep safe, efficient, and comfortable operations. In those cases, procedures and automation can even be dangerous because they are out of the context of definition. **Problem-solving** is required. However, problem-solving is a different cognitive process that does not deal with procedures following or automated systems monitoring. Problem-solving requires creativity, as well as different kinds of knowledge and experience. It requires educated common sense (Boy, 2023). At this stage, only humans can do this properly in complex situations.

Students learn to solve well-stated problems during their studies, but more time on problem-stating is needed, which is more an art than an analytical technique, even if some appropriate methods can help. It requires training, trial-and-error processes, collaboration, and repetition. This is why we allow students to take time for this process. Collaborative problem-stating and problem-solving require team building, trust, authority, and competence sharing.

Human-in-the-loop simulation and tangibility

Industry 4.0 was based on STEM (Science, Technology, Engineering, and Mathematics). Society 5.0 can only be made with HSI principles that guide human-centered design and, more generally, nature-centered design. Systems engineering and arts should go together toward SySTEAM. However, the **SySTEAM** concept can be interpreted in several ways, including systems and STEAM (i.e., Science, Technology, Engineering, Arts, and Mathematics) and systems as teams. The former connotation requires what was already presented in this paper. The latter considers the concept of human-machine teaming, when machines are equipped with artificial intelligence (AI) and become partners (Boy & Morel, 2022).

HSI is firmly based on HITLS, which enables the discovery of **emergent behaviors and properties** of the sociotechnical systems being developed. Indeed, more than conventional task analyses carried out during design and development is required to determine what people could do during operations. Digital HITLS enables observing people's activity (i.e., what people effectively do). This is the strength of digital engineering. However, since this process is performed using virtual prototypes that are not quite real in the sense of the end products, tangibility must be considered seriously. **Tangibility**, whether physical or figurative, can be seen as a distance from reality. From that point of view, students may have different perspectives in mind that can be related to realist and constructivist philosophies (Changeux & Connes, 1989): the constructivist one, which believes individual experience and problem-solving to be the keys to sound, but arguably subjective, science, and the realist one, which believes the scientific method, and more specifically, mathematics, results in objective science. A triangle, for example, can be a mental construction of a triangular stone observed on a piece of land or an object that can be mathematically defined very precisely (i.e., three non-colinear lines intersecting at three points).

Constructivists approximate substantial (tangible) observed objects by abstract (mathematical or virtual) constructs: in other words, constructivist models can be considered ontologies characterized by specific syntax and semantics. **Realists** consider that abstract objects (mathematical or virtual) and their underlying rational mechanisms may have applications in the concrete world: realist models can generally be analogs. Constructivism starts from observations of the real world and tries to find mental (cognitive) constructs that allow us to give meaning to what is perceived. Realism tries to find examples of abstractions in the real world a posteriori. Constructivist and realist approaches sometimes converge.

Students involved in our SySTEAM projects learn how to consider these two philosophies and interact with each other depending on their realist or constructivist backgrounds. They learn how to make things physically and figuratively tangible. Let us take a straightforward example (Boy, 2013). Suppose they learn the concept of derivative in mathematics illustrated by the velocity in terms of distance x and time t: v = dx/dt (Figure 2).

$$v = \frac{dx}{dt}$$

Figure 2. Velocity can be expressed in mathematical terms and by a speed indicator.

If the mathematical expression is clear from a realist viewpoint, constructivists prefer observing the speed indicator to figure out the concept of velocity. Before speed indicators were designed and used, it was accepted to start with the mathematical expression of the velocity. However, today it is possible to develop a virtual prototype of such an indicator and explain to students the incremental variations of the needle in terms of kilometers per hour, and therefore explain the distance increment on time increment ratio. In other words, physical tangibility supports figurative tangibility.

The need for exploration

Digital technology can be used in education to support learning thinking regarding physical and figurative tangibility. It profoundly influences our lives. This is why we need to understand better who current and future learners are, how they are influenced by new technology, and what this technology can bring them. Learning thinking (Boy, 2013) must be put into practice in our constantly evolving world, and experience must be accumulated and re-injected into education curricula. FlexTech Chair is currently developing an HSI approach for increasingly autonomous sociotechnical systems, where autonomy is considered for humans and machines. More specifically, we teach HSI by involving students in small projects where they must design and (partially) develop a sociotechnical system, such as the examples briefly presented in this paper. Students learn by doing, exploring a real-world problem. They incrementally learn autonomy and contribute to the design of more autonomous systems.

As already said, exploring a complex "dirty" problem requires students to learn how to state it first. This first phase involves design thinking, categorizing, synthesizing, and taking risks in designing solutions. **Risk-taking** is a vital capacity that must be learned. It requires understanding what it means to be prepared (i.e., developing educated common sense and critical thinking). The **problem-stating** process can be supported by advanced digital technology that helps visualize and materialize abstract concepts (e.g., 3D graphics and printing), fostering physical and figurative tangibility and motivating learning more about them. In addition, local linear approaches to engineering should be augmented and overseen by holistic non-linear approaches to design (i.e., complexity science should be made accessible to anyone).

Since education does not have to worry about accessing information and knowledge today, it must concentrate on **meaning** (i.e., knowledge access does not necessarily infer understanding). This is why students need to spend enough time to bring their projects to

maturity from three articulated sets of readiness levels (RL): technology (TRL: Technology Readiness Levels), organizations (ORL), and humans (HRL). We are at a stage where students constantly reshape these criteria essential to understanding and evaluating development progress. Let us further discuss HSI as a SySTEAM approach.

References

Aarrestad, F.B. et al. (2012). *Space: One giant leap for education*. TP Report. International Space University - Space Studies Program 2012. Retrieved from the Internet on June 24, 2023: https://isulibrary.isunet.edu/doc_num.php?explnum_id=413.

Boy, G.A. (2013). From STEM to STEAM: Toward a Human-Centered Education, Creativity and Learning Thinking. *Proceedings of the European Conference on Cognitive Ergonomics (ECCE, 2013),* Université de Toulouse, France. Also, in the ACM Digital Library.

Boy, G.A. (2012). What Space can contribute to Global Science, Technology, Engineering, and Mathematics (STEM) Education? *Proceedings of the 63rd International Astronautical Congress*, Naples, Italy, published by Elsevier.

Boy, G.A., Doule, O., Kiss, D.M. & Mehta, Y. (2018). Human–Systems Integration Verification Principles for Commercial Space Transportation. New Space Journal, Stanford, CA, USA, Vol. 6 No. 1. DOI: 10.1089/space.2017.0040.

Boy, G.A. (2019). STEAM for Space Leaders of Tomorrow: Human-Systems Integration as a Technique and an Art. *New Space Journal*. Vol. 7, No. 4, Stanford, CA, USA.

Boy, G.A. & Morel, C. (2022). The Machine as a Partner: Human-Machine Teaming Design using the PRODEC Method. WORK: A Journal of Prevention, Assessment & Rehabilitation. Vol. 73, no. S1, pp S15-S30. DOI: 10.3233/WOR-220268.

Boy, G.A. (2023). Epistemological Approach to Human Systems Integration. *Technology in Society Journal*. Elsevier.

Systems Thinking in Emergent Behavior Analysis Summer Internships

Kristin Giammarco[a], Michael Collins[b], John James[c], and Michael (Misha) Novitzky[c]

[a]Department of Systems Engineering, Naval Postgraduate School
[b]Laboratory for Advanced Cyber Research, National Security Agency
[c]Robotics Research Center, United States Military Academy at West Point

Abstract

In the summer of 2020, multiple Department of Defense (DOD) communities piloted a new approach to delivering an educational experience in systems thinking to college students under the leadership of the National Security Agency's National Cryptologic School. The cancellation of in-person summer internships led to a pivot to a virtual internship format in which the students learned cognitive skills for detecting, predicting, classifying and controlling emergent system behaviors from models. The summer activity was conducted over a period of about six weeks with learners participating in one of three roles: *students* from a broad range of academic backgrounds, *mentors* with expertise in problems manifesting in real systems, and *coaches* to support model development. The behavior analysis activity prompted a systems thinking approach among learners in the triad of roles that led to the realization of overlooked assumptions, undocumented requirements and unidentified risks in the modeled systems. The learning structure employed in 2020 produced such valuable insights (as asserted by the expert mentors) that the activity has been repeated every year since the pilot, and in 2023 is being held in a hybrid in-person / virtual format. Past participants have been exposed to a diverse range of mentor-selected topics such as enterprise risk management, human-robot teaming, insider threat, smart cities, risk assessment of 5G technology, coastline and maritime security, admissions process for a STEM program, and Artificial Intelligence (AI) competency assessment. Undergraduates in majors ranging from computer science to psychology contributed perspectives that broadened the thinking in each of these problem spaces. While current and past participants are primarily DOD-affiliated, the learning structure is generalizable for use in other communities, companies, schools and government agencies concerned about surprising and unwanted behaviors arising in systems and systems of systems. This paper describes the model employed to teach emergent behavior analysis as a potential formula for integration into STEAM curricula, and provides lessons learned in systems thinking education as well as emergent system behavior analysis through examples found by summer interns mentored by human-robot teaming experts at the United States Military Academy (USMA) at West Point's Robotics Research Center (RRC).

Introduction

This paper describes a teaching model for emergent behavior analysis, a new practice in systems thinking. First, we describe what emergent behavior analysis is and what it has to do with systems thinking, with examples from participating interns. Then we describe the teaching model that was tried when in-person summer internships were cancelled and refined over the next iterations. Next, we present measures of success for systems thinking education from four iterations of this activity. We conclude with lessons learned and recommendations for integration of the approach into any curricula with room to integrate a project-based systems thinking activity ranging in length from 5 weeks to an academic semester.

Background

The Naval Postgraduate School (NPS) and National Security Agency's (NSA) National Cryptologic School (NCS) have developed a systems engineering / systems thinking practice referred to as *emergent behavior analysis*. Behavior is a term that is often associated with humans and psychology, but a systems perspective studies behaviors exhibited by any system, whether human, natural, technological, social, economic or anything else that can be described in terms of a process. Broadly speaking, *behavior* is the way in which some subject conducts activity, where the subject may be a person, a natural object, a technological product, an organization, or a governing set of rules for a business or operational process. *Emergent behavior* arises when subjects interact, and some greater behavior of the whole comes into being from the combination of individual subject behaviors. There is great interest throughout the DOD, and indeed all of industry, in early exposure and control of emergent behaviors permitted by a design to enhance system safety, security, resilience, and other system-wide concerns. Until now, the challenge has been that many of these emergent behaviors are unknown until they show themselves to be possible in the operational system.

In 2015, emergent behaviors were discovered accidentally and analyzed by students ranging from high school to graduate school (Giammarco and Giles 2017) using the NPS-developed Monterey Phoenix (MP) language, approach, and tool (Auguston 2009), which was created to model system and software architectures at high levels of abstraction. Since then, we have accumulated numerous examples of these accidentally discovered behaviors, but lacked an immediate explanation for how these students were finding them. The summer of 2020 afforded us our first opportunity to observe their discovery and document a purposeful and repeatable method for the exposure and control of emergent behaviors in high-level system models. That summer, we delivered the first-ever virtual summer internship program in which college students learned cognitive skills for detecting, predicting, classifying and controlling (Giammarco 2023) emergent system behaviors from models. This internship experience yielded valuable insights, and the activity became a regular occurrence each summer. The learning structure that led to these insights, employed and refined over four iterations and now in its fifth, is described later in the paper.

The following practical description of *systems thinking* captures the essential work of emergent behavior analysis: "a holistic approach to analysis that focuses on the way that a system's constituent parts interrelate and how systems work over time and within the context of larger systems" (Lutkevich 2023). We shall demonstrate the systems thinking approach used by summer interns from the United States Military Academy (USMA) at West Point's Robotics Research Center (RRC), as they modeled and analyzed emergent behavior in human-robot teams.

Discussion of Example Student Analysis

The RRC interns were given a challenge to program maritime robots to move autonomously in a capture-the-flag competition on the water – a game that is used as a surrogate for tactical military operations and for studying human-robot teaming. The interns used MP to generate a range of plausible scenarios and outcomes based on the rules and conditions of the game. Search and rescue (SAR) scenario variants (event traces) were the focus in 2022 and included man overboard or robot malfunction events. The students, ranging from high school to college level, exposed emergent behaviors that were not planned for or considered previously (Figures 1-3), and would be unacceptable if they were to occur in the real system (Sagos et al. 2023).

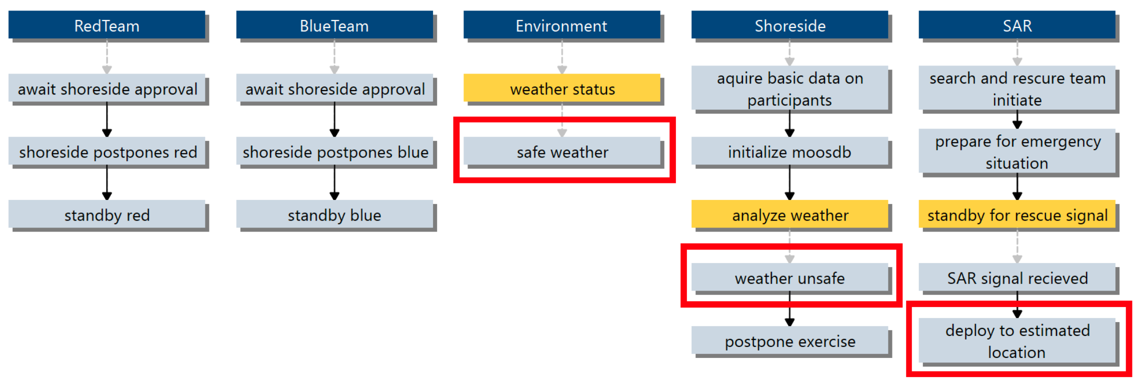


Figure 1. Shoreside mistakes safe weather as unsafe, then a SAR response occurs without having been called or a game being played.

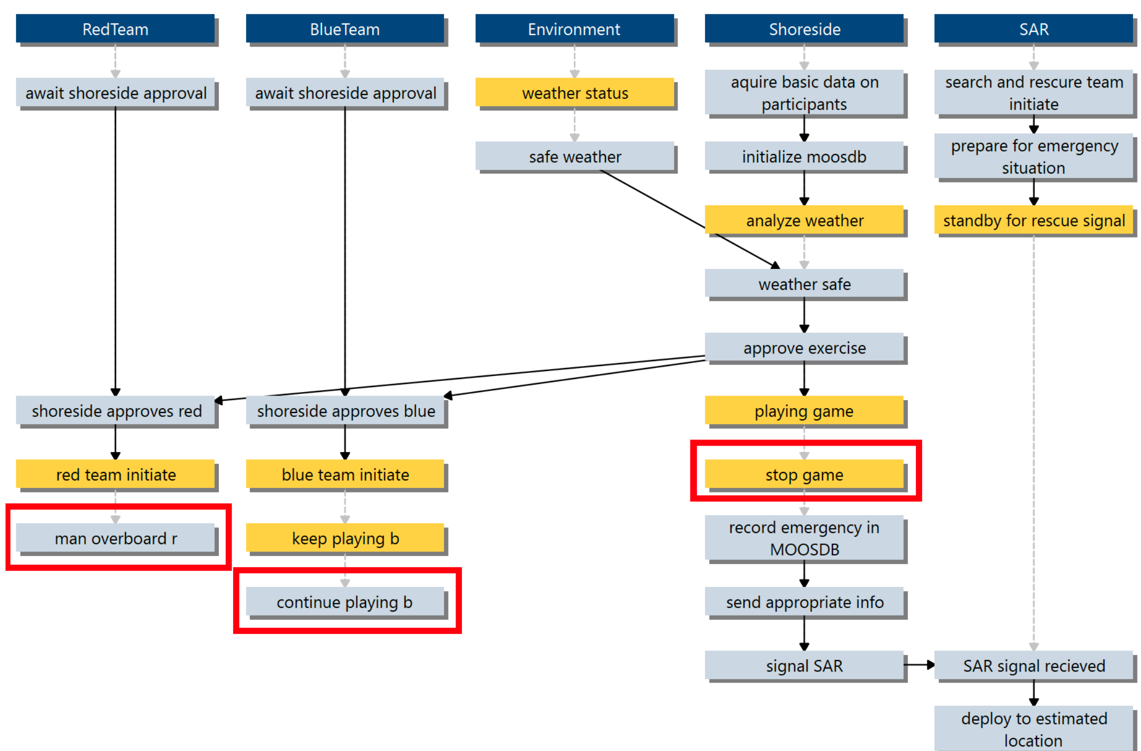


Figure 2. One of the teams has a man overboard event, but the other team continues playing the game.

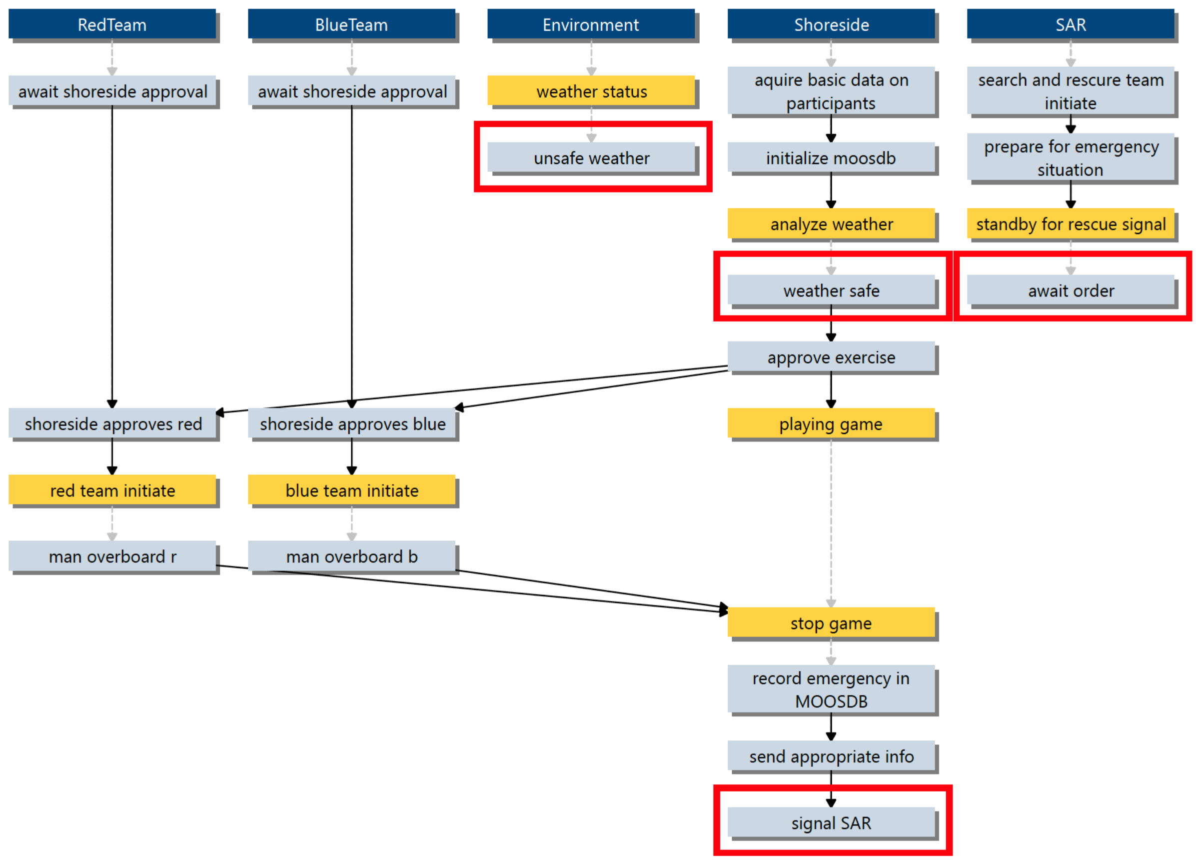


Figure 3. In this compound emergent behavior example, Shoreside misjudges the weather, two man overboard events (one on each team) happen simultaneously, and then SAR does not get the emergency signal.

Emergent behavior analysis involves creative storytelling to elicit plausible explanations for unintended traces *before* changing the model to reject the unintended traces. The following stories were composed for the traces depicted in each of the figures above (Mattson, Patel, and Sagos 2022, Giammarco and Dyer 2022).

Figure 1: the RRC interns suggested that initially the weather is safe and playable but is forecasted to become unsafe (e.g., a thunderstorm), and so the game must be postponed. SAR is then launched as a result of receiving an emergency signal from a third party (i.e., not Shoreside) concerning an event other than those considered for the gameplay. Another story about the same trace told by a graduate student (Dyer in Giammarco and Dyer 2022) was the following: the weather is safe but an insider threat occurs in which Shoreside is falsely told the weather is unsafe, causing the game to be postponed. Then, even though the game is not played, SAR resources are deployed due to a false emergency signal from the same insider threat, whose goal is to disrupt the game play and consume valuable resources. Dyer went on to identify new requirements for confirming that Shoreside itself makes the proper determination about the weather, and also that Shoreside and SAR always communicate correctly.

Figure 2: the RRC interns told a story in which shoreside approves weather is safe to play, however game is stopped because the red team has a man overboard event. Engrossed in the game

play, the blue team did not notice, and they were not informed, so they continued to play on. An emergency is recorded and SAR deploys. This story led to the addition of requirements for 1) the opposing team to stop playing if there is a man overboard event, and 2) ensuring that the game will be stopped in the event of a man overboard event.

Figure 3: the RRC interns suggested that the weather was currently unsafe, but forecasted to be safe in the future. When the weather turned clear, the game is played, then suddenly two players crash into each other resulting in two man overboard events. SAR is signaled but there were insufficient resources to conduct multiple simultaneous SAR operations. They recommended the next cohort of interns consider adding logic to estimate resources needed for conducting one or more simultaneous SAR operations. This story told by high school and college students also inspired another story by Dyer (Giammarco and Dyer 2022): The weather is unsafe but Shoreside mistakes it for safe, and approves gameplay. Part way through the game, a player on the Red Team suddenly crashes into a player on the Blue Team, resulting in two man overboard events. SAR is then signaled, but the communication method fails and SAR does not receive the signal. SAR remains in the state of awaiting an order, unaware that a signal was sent. From this story, the expert mentor of the interns was able to identify new requirements for basic weather training and also show the need for reliable communications.

These valuable insights helped the RRC and collaborating agencies identify requirements and risks that had not previously been considered. Though the interns lacked experience, they also lacked the biases and assumptions that tend to accumulate with experience. Their fresh perspectives contributed in a major way to inducing systems thinking among even their expert mentors, who learned along with the interns to think about familiar problems in new ways. The library of possible scenario variants also helped the whole team enumerate different ways things can go “right” and the many more ways things can go “wrong” in systems with many interactions, consider possible causes, and avoid or mitigate unwanted outcomes in live competition.

Internship Structure

As this paper is being written, the MP internship is in its fourth year and fifth iteration, and being held for the first time in-person with a virtual extension for remote coaches. The formula for the internship structure has interns engaged almost full time over a five-week period of time to learn about their mentor’s problem space, learn MP, write MP models, and analyze those models for emergent behavior. The internship recruits students from a broad range of academic backgrounds (e.g., computer science, cybersecurity, psychology, sociology, political science, criminal justice), mentors with expertise in problems manifesting in real systems, and coaches to support model development. Given the compressed timeframe, the mentors get relatively quick turn results that prompted a systems thinking approach leading to the realization of undocumented or unidentified assumptions, requirements and risks in the modeled systems. There is a wide breadth of application to problem spaces from technical to social to business to economic systems – examples of past mentor-selected topics include enterprise risk management, human-robot teaming, insider threats, smart cities, risk assessment of 5G technology, admissions process for a STEM program, coastline and maritime security, and Artificial Intelligence (AI) competency assessment. Figure 4 shows how these topics are structured with team member roles used in these internships.

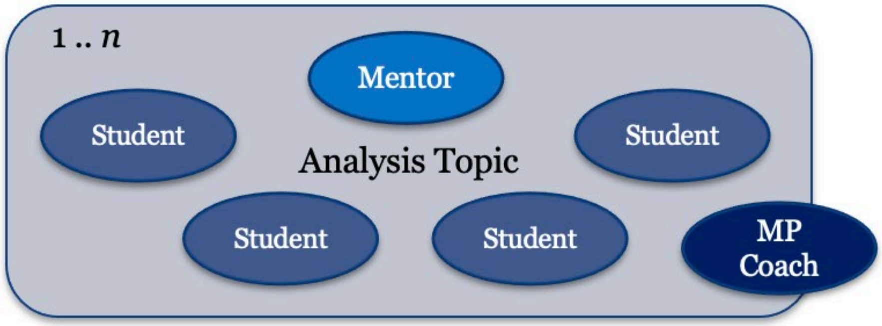


Figure 4. Each of 1..*n* analysis topics has a workforce mentor and several assigned students (ideally 3-4). MP modeling coaches circulate among the teams. Though the ideal ratio is one coach per team, we have found that one coach can often handle several teams as the students alternate between receiving modeling advice and then working to integrate it.

Selected students (interns) work on problems in small teams with expert mentors and learn how to use MP at the basic and intermediate levels from MP coaches.

- They create simple but informative MP models of interest to the sponsor that produce example instances of system behavior and interactions
- They practice the human-machine partnership that enables exposure and control of emergent behaviors and requirements discovery through the process of MP modeling
- They learn to contemplate and predict potential future states of behavior and systemic consequences using MP scenarios as creative storytelling prompts
- They learn to apply systematic and formal thinking to the development, verification, and validation of system architectures

Students from previous internship cohorts often return in the role of an MP coach and acquire advanced skills in MP analysis as a result of the additional exposure to other student models, which often contain more model structures than can be seen in a singular team's model. They may also learn how to use MP in risk analysis, schedule planning, resource utilization, cost analysis, pattern analysis and architecture view generation (e.g., activity diagrams, component diagrams, and state diagrams).

Mentors recruited from active workforce gain further insight into their own system or subject area of expertise.

- They hold a minimum of twice-weekly meetings with their students
- They familiarize their team of students with their system and its problem space
- They share or create with the students a step-by-step narrative of a normal, expected sequence of events for an operation or work flow
- They engage the students in critical thinking about the problem, asking probing questions such as "why do you think that is?" and "what could go wrong"?
- They answer general questions about what it is like to work in their field of expertise
- They receive regular updates on the progress of the MP model of their problem, and remind the students to use "customer language" that assumes no familiarity with MP

New mentors receive advice and coaching from mentors with experience from previous internship events.

MP coaches recruited from graduate programs and past internships gain further insight into their own research or subject area of interest.

- They are invited to participate in MP modeling lessons throughout the program to increase their own MP skills
- They attend twice-weekly meetings to help the students express behavior for their assigned topic in the MP language
- They share with the students common model errors and bugs they have seen in other teams/models, and advice on how to fix them
- They guide the students as they develop work products and help them extend their "normal" MP models to include "off-normal" scenarios
- They participate in weekly "coach the coach" meetings where they discuss the more challenging bugs or problems with peers

New coaches have access to experienced coaches and receive advice and coaching on their own MP modeling projects.

A typical day on internship starts with an agenda-setting morning meeting, followed by a morning session composed of either a modeling lesson or team breakout sessions with mentors or modeling coaches, a break for lunch, and then an afternoon session followed by a closing meeting at which teams outbrief their progress for the day (Figure 5). The current internship (cohort 5) has a "Fun Friday" featuring a different facility tour each week, involving local labs and research/engineering spaces, museums, academies and workforce interaction opportunities.

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Time
0800	Networking Time	Networking Time	Networking Time	Networking Time	Facility Tour	0800
0830	Morning Meeting: Daily Plans & Advice	Morning Meeting: Daily Plans & Advice	Morning Meeting: Daily Plans & Advice	Morning Meeting: Daily Plans & Advice		0830
0900	Meet with Team / Mentor	Monterey Phoenix Lesson	Meet with Team / Mentor	Monterey Phoenix Lesson		0900
0930						0930
1000						1000
1030		Meet with Team / MP Modeling Coach		Meet with Team / MP Modeling Coach		1030
1100						1100
1130						1130
1200	Submit Team's Engineering Notebook Entry + Lunch	Submit Team's Engineering Notebook Entry + Lunch	Submit Team's Engineering Notebook Entry + Lunch	Submit Team's Engineering Notebook Entry + Lunch		1200
1230						1230
1300						1300
1330	Meet with Team / Mentor	Meet with Team / MP Modeling Coach	Meet with Team / Mentor	Meet with Team / MP Modeling Coach		1330
1400						1400
1430						1430
1500						1500
1530						1530
1600	Afternoon Meeting: Daily Recap	Afternoon Meeting: Daily Recap	Afternoon Meeting: Daily Recap	Afternoon Meeting: Daily Recap		1600
1630	Dismissal	Dismissal	Dismissal	Dismissal		1630
1700						1700

Sessions that everyone attends.

Figure 5. An example week's agenda (mid-program).

A general orientation is held on the first day of the program, and a showcase event is held on the last day. The showcase event is attended by all internship participants and invited guests (to include organizational leadership), who receive an overview of the program and a summary of accomplishments of the cohort followed by a 10-15 minute presentation by each team.

Measures of Success

The learning structure has demonstrated itself to be effective in delivery and well-received by learners. While no controlled research study has been done, the first iteration had an average net promoter score of 8.54 from an informal survey at the conclusion (28 respondents). We have collected informal testimonials for use in newsletters and recruiting material. For example, an intern shared:

"Within a day or two, I understood how to create a basic model schema to generate hypothetical behavior scenarios, which, in a sense, do nothing more than help tell a story… But MP also sometimes shows a story that is sensical but unanticipated—or emergent—that makes you think, 'Yeah, actually, that could happen. Why didn't I think of that?' "

Expert mentors have shared:

"It was a privilege mentoring small teams through critical thinking using Monterey Phoenix. Graphically modeling the problem and solution spaces almost always led to creative A-Ha moments which were very rewarding to witness and implement."

"The challenge with MP was figuring out the approach, methodology, and the way to frame the questions for the tool. Once that was accomplished, then asking questions and the resultant models provided insights very quickly. With the first summer program, we struggled for weeks trying to figure how to properly frame the problem for MP. Once we did we found the model provided unforeseen insights in a matter of days. Those insights made that summer's program worth the initial struggle. The second summer's program was not as much struggle with the tool as the previous summer and the insights from that problem were even more insightful."

MP model coaches (graduate students) have shared:

"It is rewarding to be able to assist new users of the language and tool, while also further enhancing my MP skillset. During last summer's internship specifically, I really enjoyed sharing recommendations for structuring initial models, assisting with debugging, and seeing the participants discover emergent system behaviors in real-time. Also, after discussing conditional coordination and MP state machine building with the interns, I have found new ways to apply these techniques to my own MP models and research projects. I look forward to collaborating with the new teams during this year's MP Summer Program."

"Coaching others in MP allows you to not only bring your experienced perspective to the table, but broaden the perspective of some of the rising thinkers and leaders of the next generation. Coaching a team in MP takes your passion for a particular subject and dives deep into a

conversation understanding the relationships within that subject and showing how simple changes can make a massive impact on outcomes."

The layering of different experience levels into the internship framework – from student interns, to MP model coaches, to expert mentors – provided an environment in which everyone was able to start comfortably from where they were and advance their skills, most especially in systems thinking, as these shared insights suggest. Besides informal student and mentor feedback, the metric we have been using to measure success has been the number of "surprising" emergent system behaviors discovered by each cohort in analysis (Table 1).

Table 1. Internship Statistics

Cohort	*Year*	*# Interns*	*# Topics*	*# Surprising Emergent Behaviors*
1	2020	60	5	11
2	2021	32	8	11+
3	2021	22	5	10
4	2022	11	4	4
5	2023	28	7	in process

Three of these surprising emergent behaviors from cohort 4 were exemplified in Figures 1-3. The value of surprising behaviors is relative to the one learning about a behavior they did not realize was possible. For example, a student with less experience may be surprised by something that does not surprise an experienced mentor. But when an experienced mentor is surprised and learns something about an area in which they are a well-regarded expert, an entire organization often learns and real system designs benefit, as the mentor testimonials suggest.

Summary

Since 2020, a total of 125 interns and 22 topics have produced dozens of emergent behaviors in systems from some very different domains leading to the identification of latent risks and undocumented assumptions, resulting in a maturing methodology for emergent behavior analysis and high praise for the program from senior leaders and sponsoring organizations. From four complete iterations and the fifth in progress, some of the key lessons have been the following:

- Keep the team sizes small. Groups with greater than 4 students tended to have some dominant students that participated all the time leaving others with less openings to contribute. Emergent behavior analysis in particular benefits from all team members being heard.
- Encourage students to take on a role of "smart ignoramus" (Berry 1998). Even those who are ignorant in the subject matter can use their intelligence to ask basic questions and challenge assumptions.
- Have a mix of academic backgrounds on each team if possible. Students in different academic programs tend to share different perspectives in the storytelling, and the team's analysis benefits from this divergence.
- Have a persistent online environment even when using in-person delivery. This environment serves as a central place for students to post their work, and for remote coaches to retrieve their files to provide feedback. For example, we used Microsoft

Teams to screen-share a General channel meeting over the projector so that remote participants could see the room, and in-person participants could see the remote participants and their chat messages. We also created a Teams channel for each team and encouraged them to use the Files area to store their documents and models and to keep a channel meeting open in their breakout rooms to enable remote model coaches to find and advise them.

- Provide clear expectations for activity before every breakout session and remind the students to post draft work in the shared area where it can be accessed for feedback.
- Remind the students frequently to keep the behaviors in their model at the high level, and as solution-neutral as possible until the problem is well understood.

This model for learning emergent behavior analysis can be integrated into project-based systems thinking curricula. Although our implementation was full time over 5 weeks, the format could be spread out over a longer period of time such as an academic quarter or semester. While the compact version holds and concentrates the attention of participants, it can be difficult to find 5 straight weeks for any activity outside of internships and summer camps. An adjusted schedule may use a Tuesday/Thursday or a Monday/Wednesday/Friday scheduling. The learning structure described has worked well for conducting productive emergent behavior analysis, and the results we have had with it suggests it may be of some value to schools, communities, companies, and government agencies that can identify problems of interest in which surprising and unwanted behaviors may arise in systems and systems of systems.

Acknowledgements

The authors would like to acknowledge the support of the NSA for sponsoring cohorts 1, 2, 3 and 5 and the Naval Research Program Office for sponsoring cohorts 4 and 5 of the Monterey Phoenix Internship Program.

References

Auguston, Mikhail. 2009. “Monterey Phoenix, or how to make software architecture executable,” in Proceedings of the 24th ACM SIGPLAN conference companion on Object oriented programming systems languages and applications. Orlando, FL: ACM, 2009, pp. 1031–1038.

Berry, Daniel. 1998. “Formal Methods: The Very Idea, Some Thoughts About Why They Work When They Work.” Proceedings of the 1998 ARO/ONR/NSF/ARPA Monterey Workshop on Engineering Automation for Computer Based Systems, Monterey, CA, pp. 9-18.

Giammarco, Kristin. 2023. "Exposing and Controlling Emergent Behaviors Using Models with Human Reasoning," In *Emergent Behavior in System of Systems Engineering*, edited by Larry Rainey and O. Thomas Holland. pp. 23-61. Boca Raton, FL: CRC Press Taylor & Francis Group.

Giammarco, Kristin and Kathleen Giles. 2017. “Verification and validation of behavior models using lightweight formal methods.” Proceedings of the 15th Annual Conference on Systems Engineering Research. Redondo Beach, CA. March 23-25, 2017. Best paper award.

Giammarco, Kristin and Pamela Dyer. 2022. “Acquisition Decision Support with Monterey Phoenix.” Technical Report NPS-SE-22-007. Monterey, CA, USA.

Lutkevich, Ben. 2023. “Definition: systems thinking.” Accessed July 18, 2023 [Online]. Available: https://www.techtarget.com/searchcio/definition/systems-thinking?Offer=abt_pubpro_AI-Insider

Mattson, Luke, Vishal Patel, and Michael Sagos. 2022. "Human-robot teaming: Sar expansion," MPVIP Cohort 4 Showcase Presentation, United States Military Academy Robotics Research Center, West Point, NY, USA, Summer 2022.

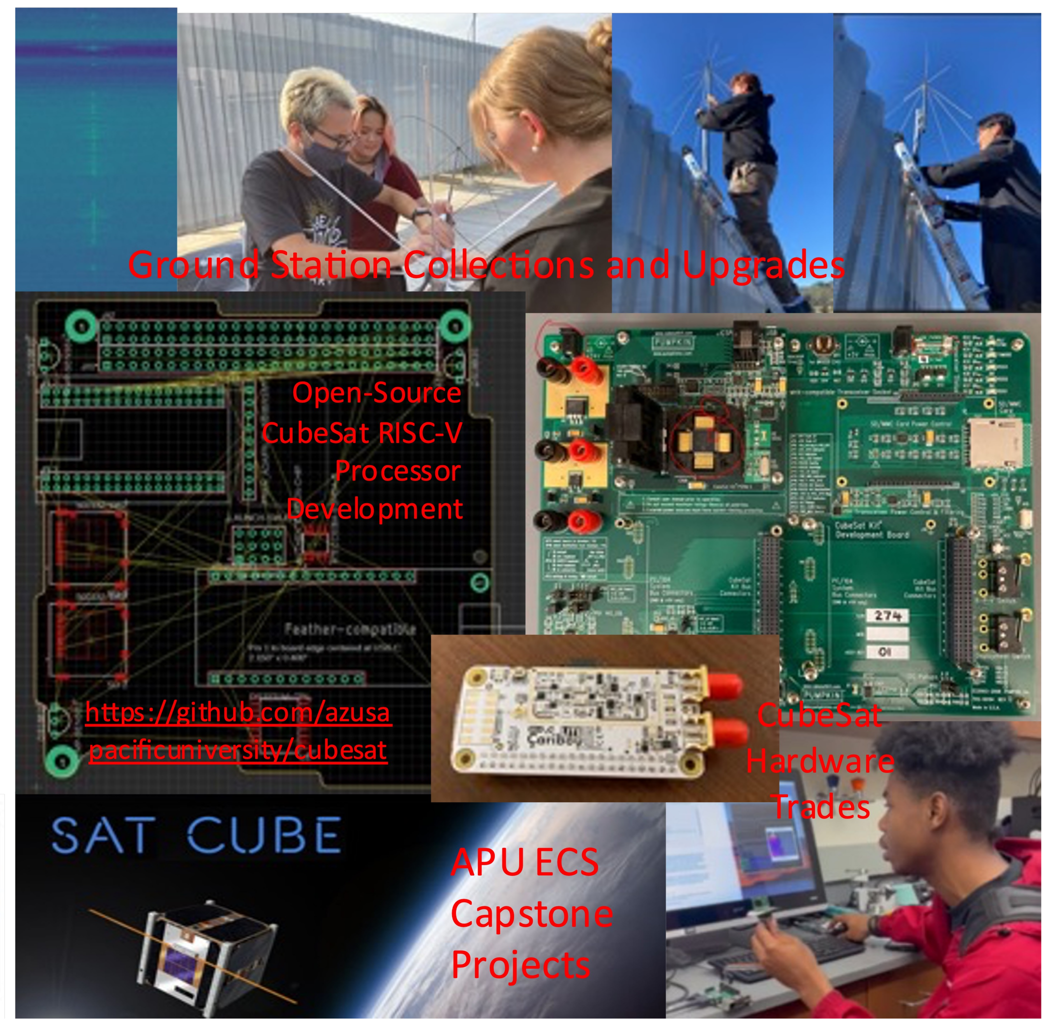
Sagos, Michael, Luke Mattson, Vishal Patel, Kristin Giammarco, Pamela Dyer, Michael (Misha) Novitzky, John James, Robert Semmens, Michael Collins, and Stuart Harshbarger. 2023. "Behavior Analysis of Search and Rescue Operations Employing Human-machine Teaming," Proceedings of the SPIE Defense + Commercial Sensing Conference, Orlando, FL April 30 – May 4, 2023.

Azusa Pacific University (APU) Engineering and Computer Science (ECS) CubeSat Program

James D. Johansen, PhD, jjohansen@apu.edu, J.R. Marshall, MS, jmarshall@apu.edu

APU ECS CubeSat Program Highlights

- Stood up a dedicated CubeSat lab.
- Installed a new receive antenna.
- Exploring CubeSat hardware trades.
- Designing a CubeSat RISC-V open-source processor and doing PCB development.
- Demonstrated collections of AMSAT and SatNOGS assets from our ground station.
- Continued CubeSat-related development in Engineering and Computer Science Capstone senior projects.



Collaboration

- APU ECS's industry advisory board also provides guidance to help steer the recommended path forward in this effort.
- APU ECS thanks the Cal Space Grant for support
- Collaboration and outreach with high schools are being done.
- Plus, colleagues from NASA's Jet Propulsion Laboratory (JPL) and NASA Goddard have graciously provided helpful consultation on our efforts.

AZUSA PACIFIC UNIVERSITY

NASA

JPL Jet Propulsion Laboratory California Institute of Technology

CALIFORNIA SPACE GRANT

NASA Goddard SPACE FLIGHT CENTER

Ground Station

- Through close collaboration between faculty and students, an operational CubeSat ground station ca collect and process AMSAT (www.amsat.org) and SatNOGS (https://satnogs.org) satellite data and report it to these organizations as a part of their volunteer cooperative ground station partners.
- APU has been on the leaderboard for these organizations regarding satellite collections and reporting.

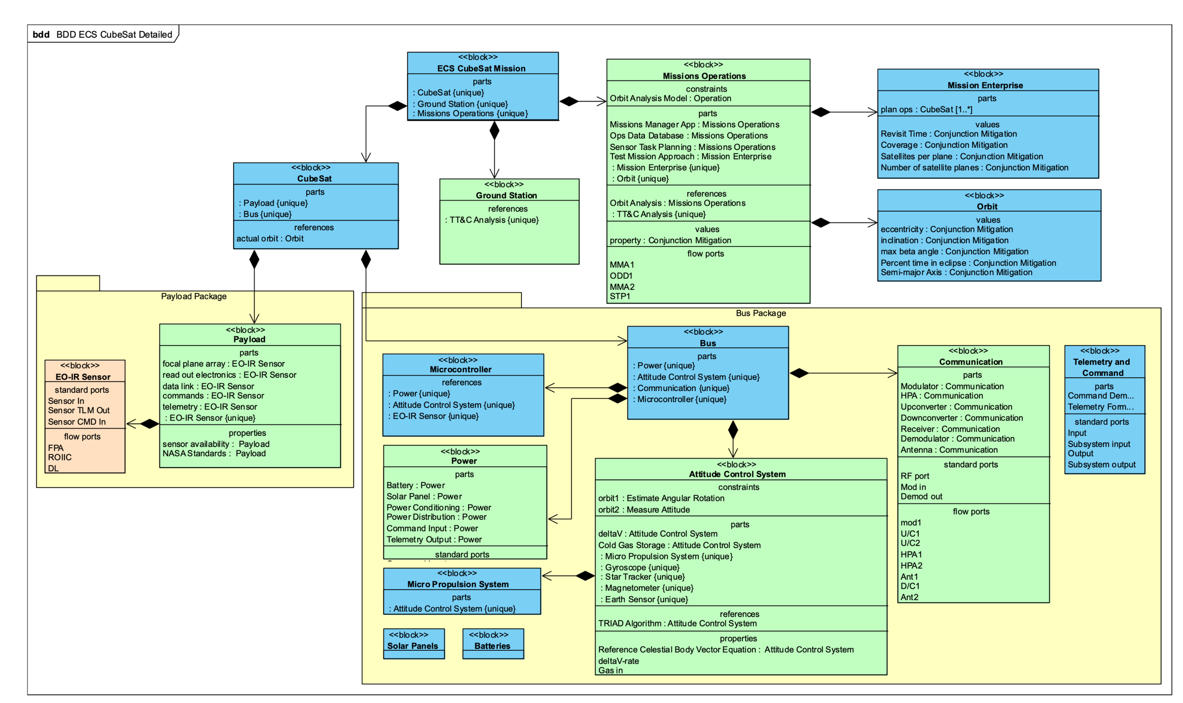
AMSAT AMATEUR RADIO IN SPACE

SatNOGS

Systems Engineering

As APU ECS prepares to create a 1U CubeSat (a 10 cm cube satellite), systems engineering trades with the systems modeling language (SysML) and other tools, performance modeling, and prototyping of hardware modules continue.

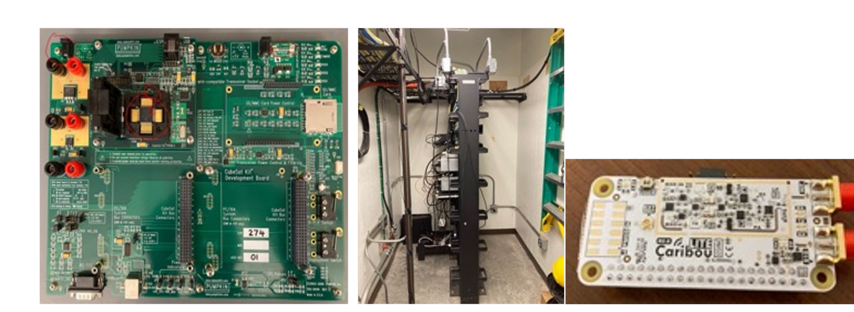
- This enables various systems engineering trades to explore model-based systems engineering (MBSE).

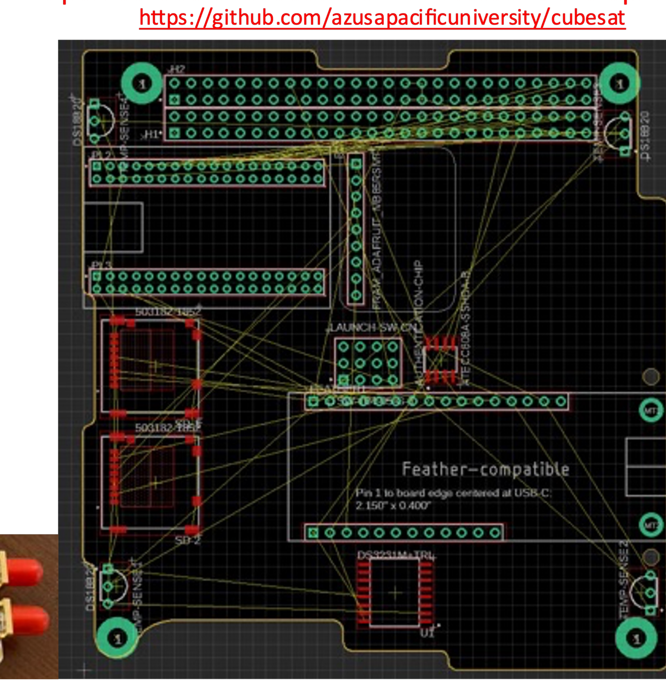


Hardware

- CubeSat hardware trades are ongoing.
- Most noteworthy is a CubeSat reduced instruction set computer (RISC-V) open-source processor development, including the printed circuit board (PCB) development.

Open-Source CubeSat RISC-V Processor Development
https://github.com/azusapacificuniversity/cubesat

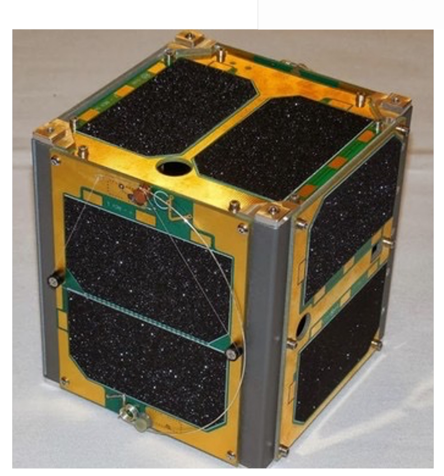


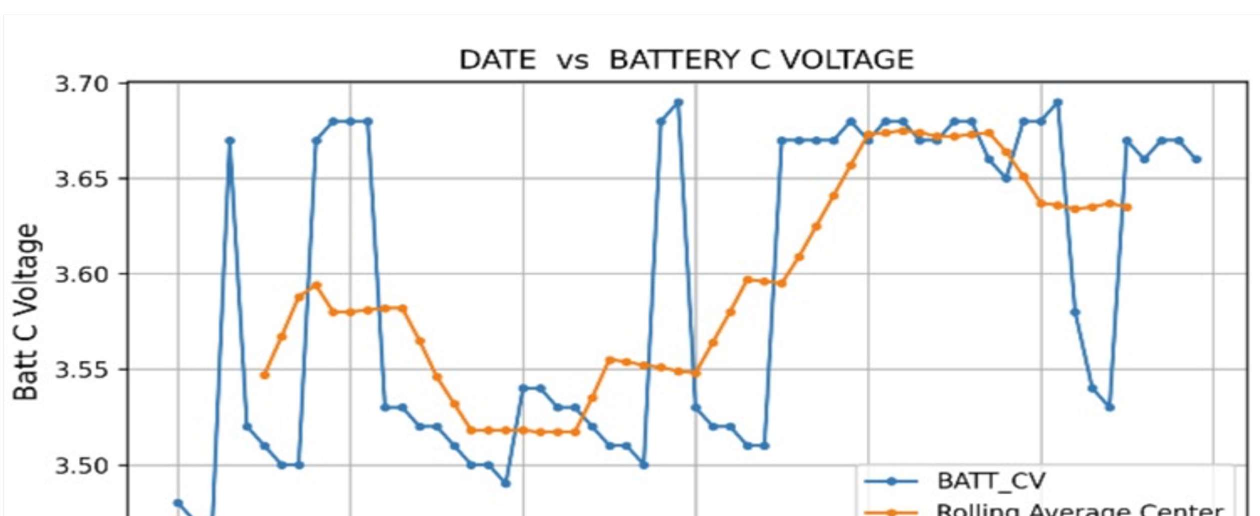


Data Analysis

- Data analytics is being done looking at performance trends of various CubeSat assets.
- This includes postmortem characterization of end-of-life CubeSats.

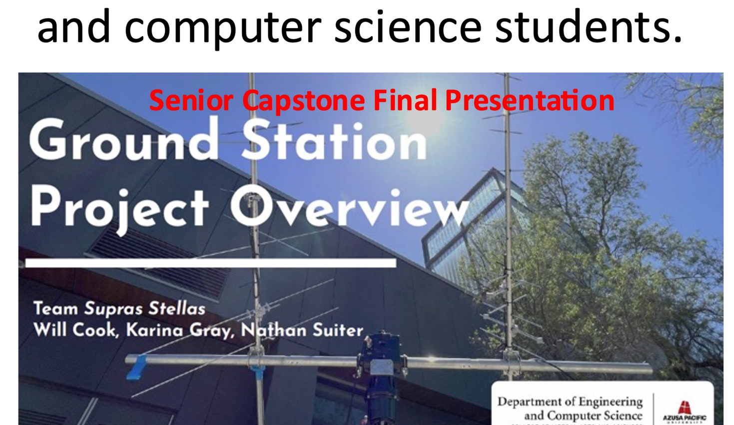
Fox-1C CubeSat

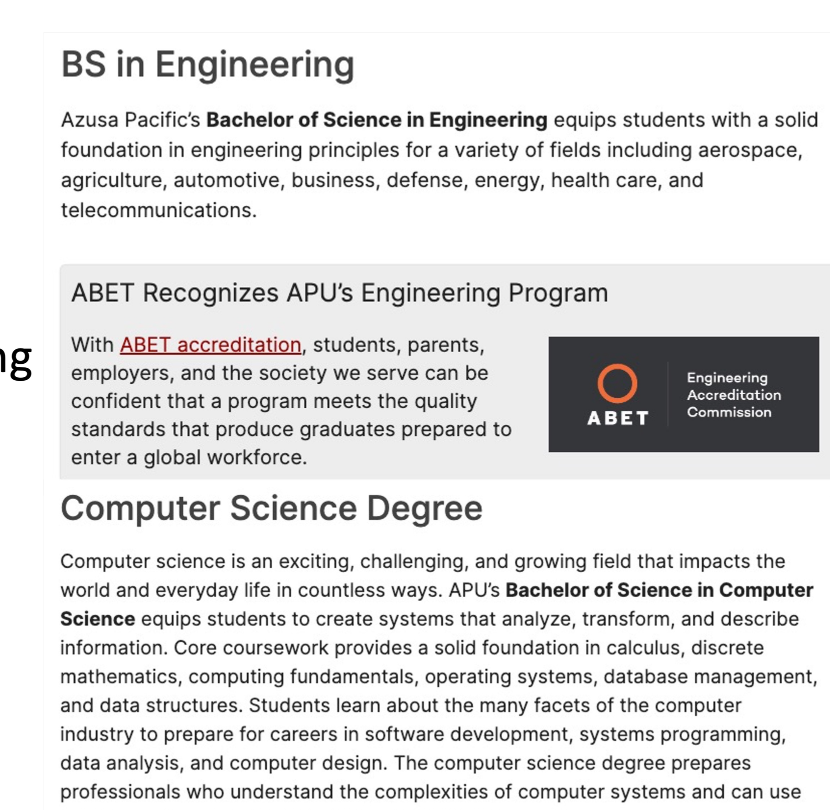




Coursework

- Several core curricular classes have been tailored to allow students to focus on CubeSat-related development.
- This is especially done in the senior capstone courses for both engineering and computer science students.





BS in Engineering

Azusa Pacific's **Bachelor of Science in Engineering** equips students with a solid foundation in engineering principles for a variety of fields including aerospace, agriculture, automotive, business, defense, energy, health care, and telecommunications.

ABET Recognizes APU's Engineering Program

With ABET accreditation, students, parents, employers, and the society we serve can be confident that a program meets the quality standards that produce graduates prepared to enter a global workforce.

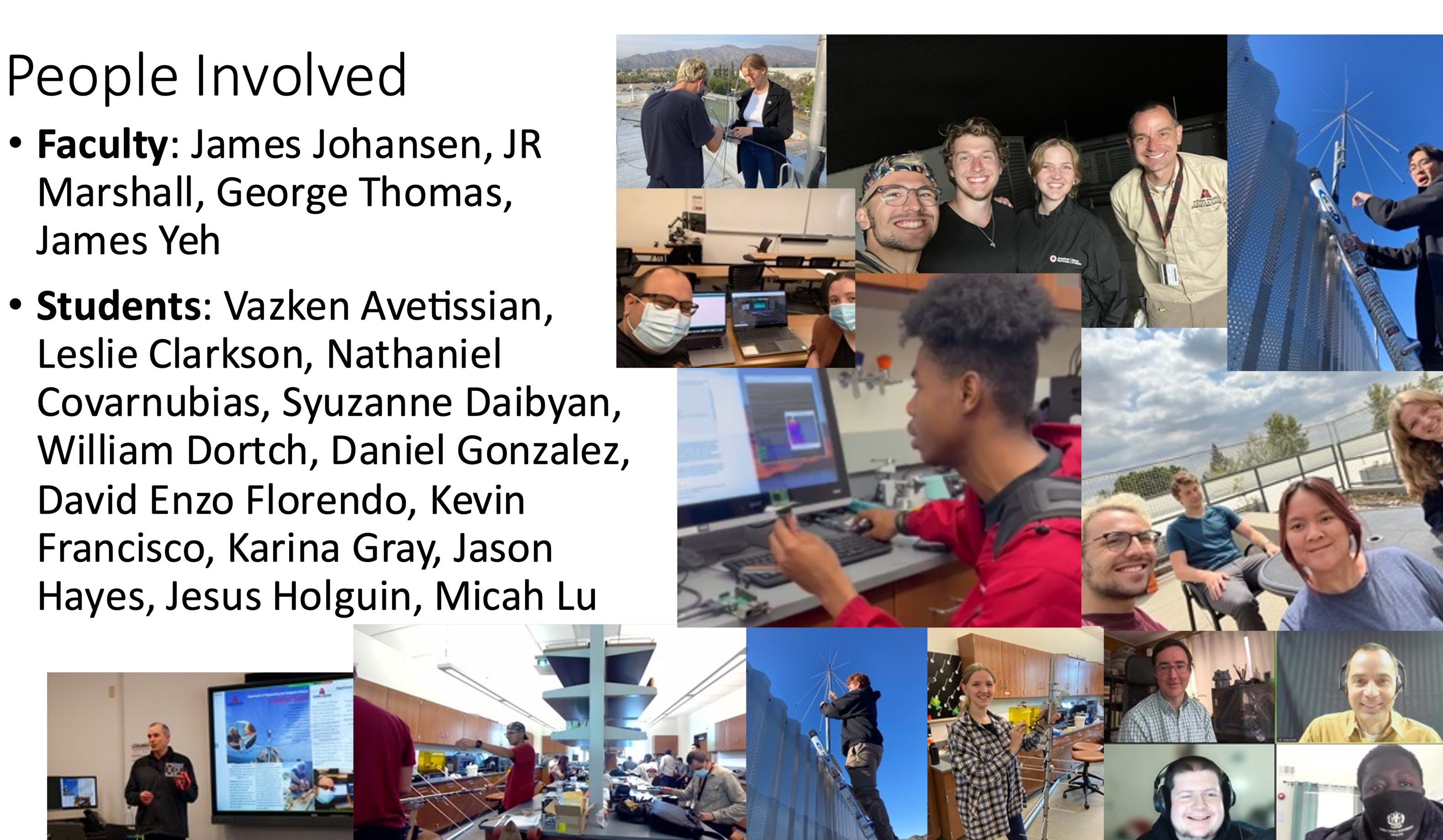
ABET Engineering Accreditation Commission

Computer Science Degree

Computer science is an exciting, challenging, and growing field that impacts the world and everyday life in countless ways. APU's **Bachelor of Science in Computer Science** equips students to create systems that analyze, transform, and describe information. Core coursework provides a solid foundation in calculus, discrete mathematics, computing fundamentals, operating systems, database management, and data structures. Students learn about the many facets of the computer industry to prepare for careers in software development, systems programming, data analysis, and computer design. The computer science degree prepares professionals who understand the complexities of computer systems and can use them to address pressing and intricate problems.

People Involved

- **Faculty**: James Johansen, JR Marshall, George Thomas, James Yeh
- **Students**: Vazken Avetissian, Leslie Clarkson, Nathaniel Covarnubias, Syuzanne Daibyan, William Dortch, Daniel Gonzalez, David Enzo Florendo, Kevin Francisco, Karina Gray, Jason Hayes, Jesus Holguin, Micah Lu



Safety Third: A Case Study for a Project-Based Approach to Systems Engineering Education

Rocket Car Case Study

1. Assign Roles

Project Kickoff: Divide teams and assign student roles

Project Manager	Lead Designer	Test and Evaluation Manager
Master Scheduler	Manufacturing Lead	Configuration Management Specialist
Cost Estimator	Software Lead	Quality Manager
Requirements Manager	EVM Manager	Cybersecurity Manager
Decision Analysis Lead	Risk Manager	Lead Systems Engineer

2. Requirements

Students develop requirements and Statement of Work

Requirements

- Car must maintain a straight trajectory relative to the goal point.
- Car must be able to hold A, B, or C size rocket motors.
- Car must use an arduino to ignite the motors.
- Car must have an accelerometer to gather data.
- Car must be built within the specified budget.
- All workers keep to the schedule and resources provided.

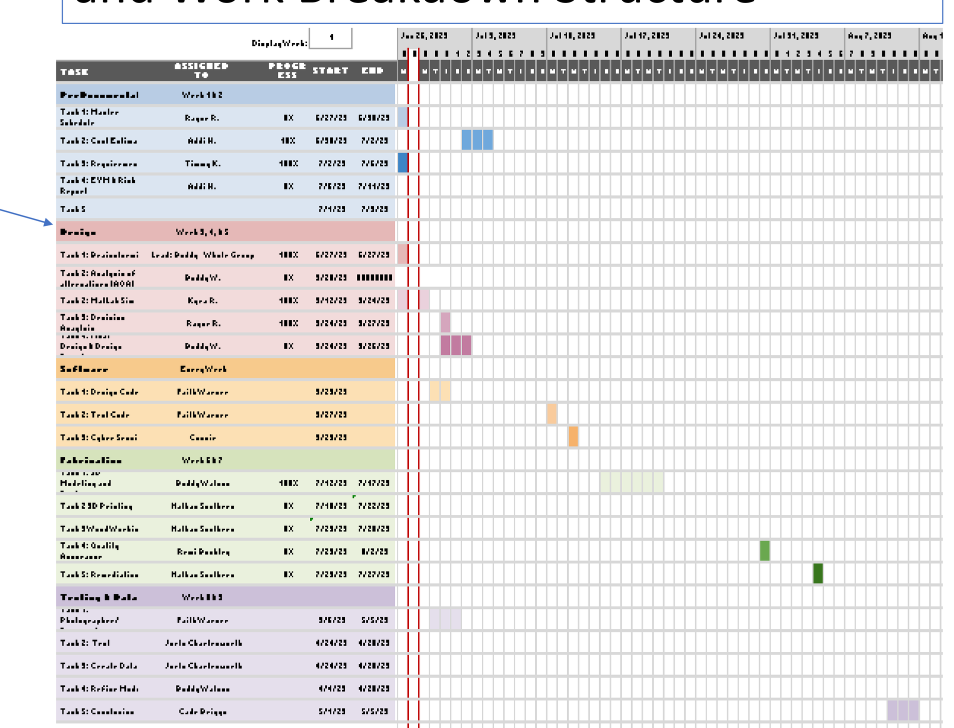
3. Analysis of Alternatives

Students develop three viable concepts and conduct AoA

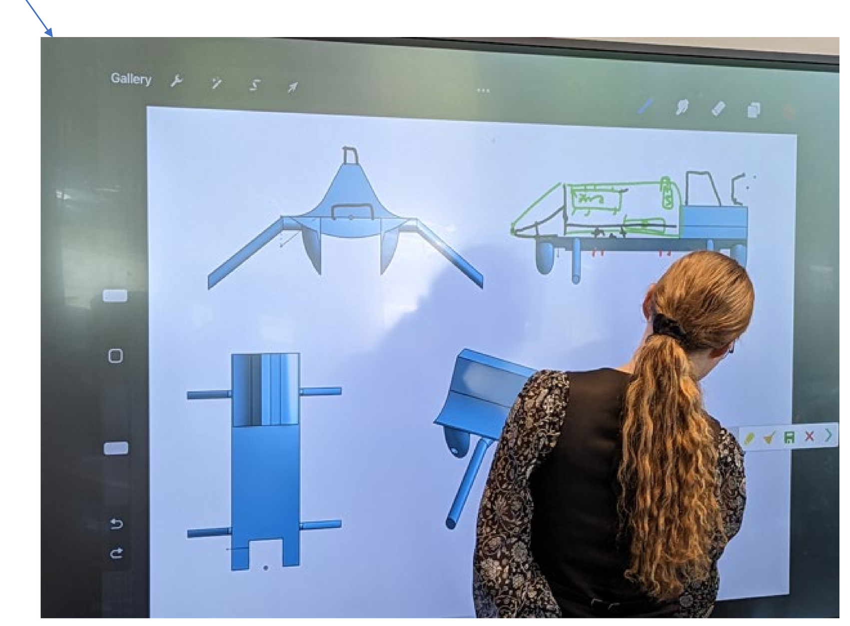
	(1-5) Design1	(1-5) Design2	(1-5) Design3	weight
Safety	5	5	1	0.35
Cost	4	4	3	0.15
Schedule/Time	4	4	0	0.2
Function/Integrity	4	3	3	0.2
Speed	4	3	4	0.1
Total	4.35	4.05	1.8	1

4. Project Planning

Students develop budget, schedule, and Work Breakdown Structure

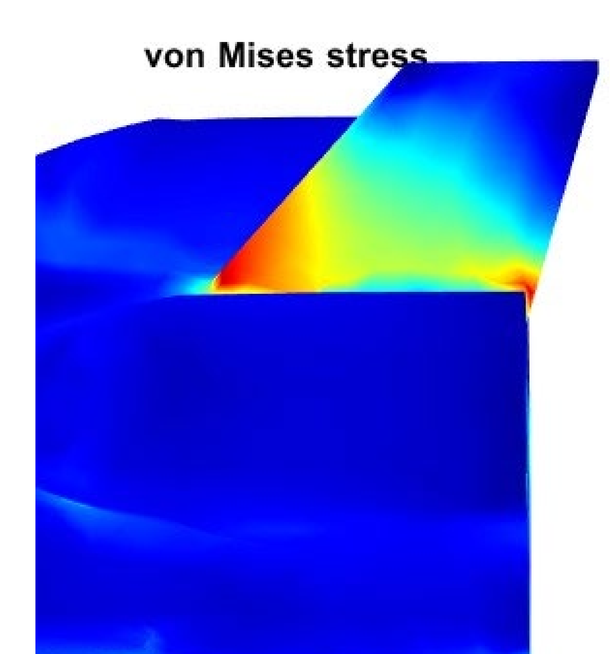


5. Initial Design



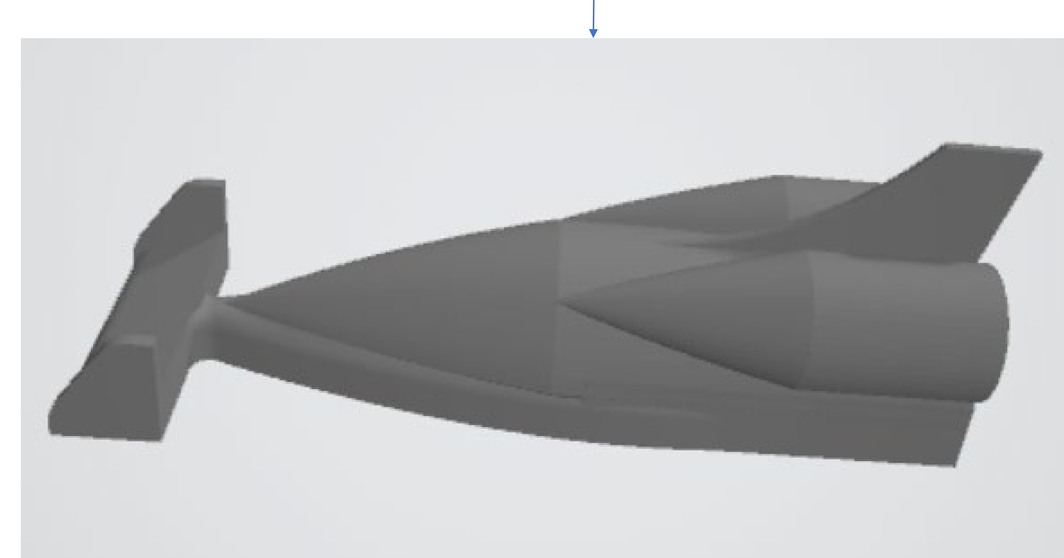
Students begin design process

6. Simulation



Students conduct initial modelling and simulation

7. Final Design



Students refine and finalize design based on simulation and early analysis results

8. Fabrication

Students fabricate final design

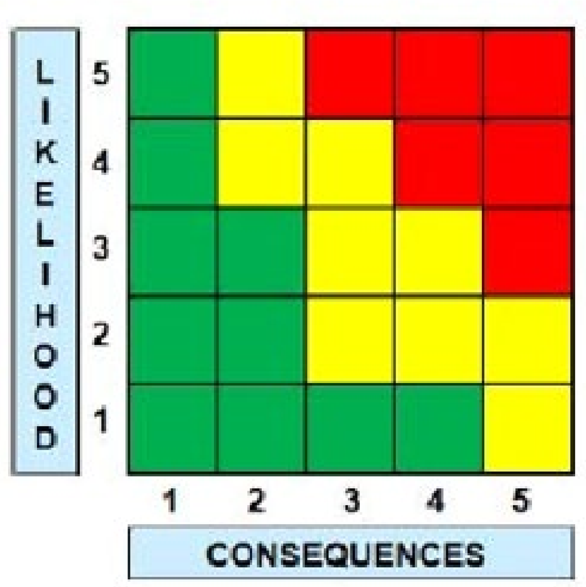
9. Earned Value

SV = BCWP - BCWS

CV = BCWP - ACWP

Students conduct EVM using actual cost and schedule

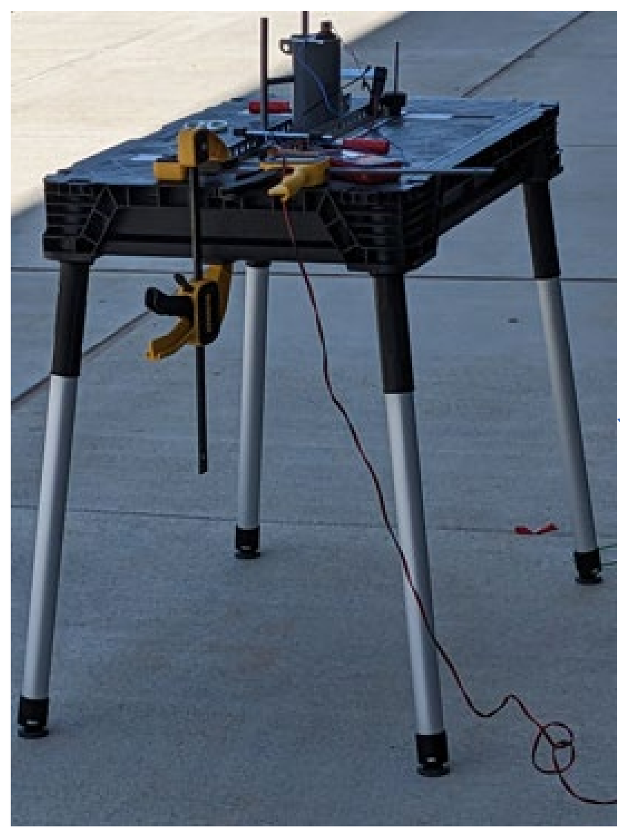
10. Risk, Quality, Safety



Students conduct risk management and QS activities

11. Test and Evaluation

Students test designs and gather data



12. Analysis

Students conduct basic analysis of test results

	Variable 1	Variable 2
Mean	161	145.1667
Variance	32	12.56667
Observations	6	6
Pooled Variance	22.28333	
Hypothesized Mean Difference	0	
df	10	
t Stat	5.809555	
P(T<=t) one-tail	8.54E-05	
t Critical one-tail	1.812461	
P(T<=t) two-tail	0.000171	
t Critical two-tail	2.228139	