INSIGHT

This Issue's Feature:

Systems Engineering for Sustainability

MBCD Framework Modifications

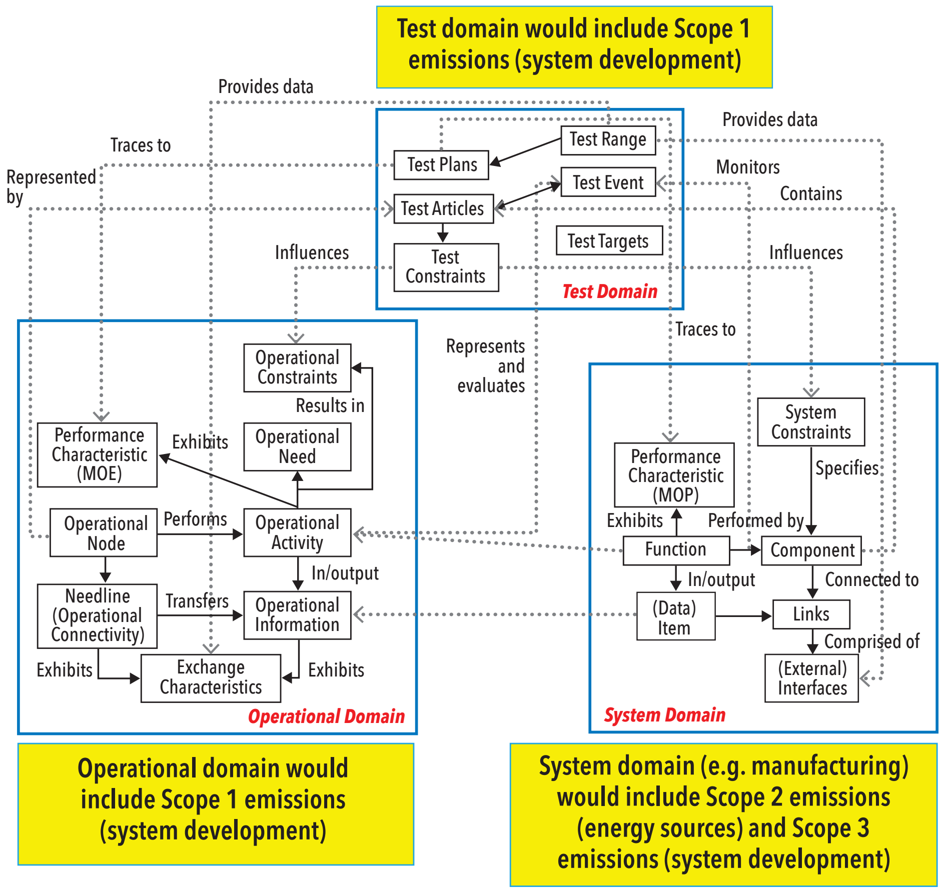

Illustration credit: from the article
Carbon Considerations for Systems Evolution
by David Flanigan and Kevin Robinson (page 39)

FEBRUARY 2024
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A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

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Inside this issue

About This Publication

INFORMATION ABOUT INCOSE

INCOSE's membership extends to over 20,000 members and CAB associates and more than 200 corporations, government entities, and academic institutions. Its mission is to share, promote, and advance the best of systems engineering from across the globe for the benefit of humanity and the planet. INCOSE charters chapters worldwide, includes a corporate advisory board, and is led by elected officers and directors.

For more information, click here:
The International Council on Systems Engineering
(www.incose.org)

OVERVIEW

INSIGHT is the magazine of the International Council on Systems Engineering. It is published four times per year and features informative articles dedicated to advancing the state of practice in systems engineering and to close the gap with the state of the art. ***INSIGHT*** delivers practical information on current hot topics, implementations, and best practices, written in applications-driven style. There is an emphasis on practical applications, tutorials, guides, and case studies that result in successful outcomes. Explicitly identified opinion pieces, book reviews, and technology roadmapping complement articles to stimulate advancing the state of practice. ***INSIGHT*** is dedicated to advancing the INCOSE objectives of impactful products and accelerating the transformation of systems engineering to a model-based discipline.
Topics to be covered include resilient systems, model-based systems engineering, commercial-driven transformational systems engineering, natural systems, agile security, systems of systems, and cyber-physical systems across disciplines and domains of interest to the constituent groups in the systems engineering community: industry, government, and academia. Advances in practice often come from lateral connections of information dissemination across disciplines and domains. ***INSIGHT*** will track advances in the state of the art with follow-up, practically written articles to more rapidly disseminate knowledge to stimulate practice throughout the community.

ARTICLE SUBMISSION insight@incose.net

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- December 2024 – 1 September 2024
- February 2025 issue – 1 November 2024

For further information on submissions and issue themes, visit the INCOSE website: www.incose.org

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FROM THE EDITOR-IN-CHIEF

William Miller, insight@incose.net

We are pleased to announce the February 2024 *INSIGHT* issue published cooperatively with John Wiley & Sons as the systems engineering practitioners' magazine. The *INSIGHT* mission is to provide informative articles on advancing the practice of systems engineering and to close the gap between practice and the state of the art as advanced by *Systems Engineering*, the Journal of INCOSE also published by Wiley.

The issue theme is *systems engineering for sustainability* in support of the future of systems engineering (FuSE) initiative www.incose.org/fuse to realize the *Systems Engineering Vision 2035* published by INCOSE in 2022 www.incose.org/publications/se-vision-2035. Chapter 1 of the vision describes the global context for systems engineering including the 17 United Nations sustainable development goals that serve as a proxy for human needs and six global megatrends for the future of systems also with emphasis on sustainability. Chapter 2 describes the current state of systems engineering and chapter 3 describes the envisioned future state. Chapter 4 describes a path to realize the vision, enumerating nine systems engineering challenges as well as 44 recommendations to the systems engineering community, and a roadmap of goals for 2025, 2030, and 2035 for applications, practices, tools and environment, research, and competencies. The FuSE initiative is currently structured as four project streams to realize the vision: vision (refinement) and road mapping, foundations, methodologies, and application extensions. Sustainability is crosscutting across these four streams. Examples of INCOSE engagement in sustainability is the smart cities initiative www.incose.org/smartcities.

This issue of *INSIGHT* features relevant articles selected from the 2023 INCOSE International Symposium by authors representing all three INCOSE sectors: Americas; Europe, Middle East, and Africa (EMEA); and Asia-Oceania. Our intent is to encourage and stimulate our systems engineering community to appreciate the focus on sustainability as evidenced by the articles contributed by authors working in industry and academia in response to signals from governments and their agencies. We thank the authors and their sponsoring organizations. We are pleased by the diversity of systems engineering methods and tools applied in the articles. Articles referencing specific research and commercial systems engineering tools and products does not represent *INSIGHT* and INCOSE endorsement of referenced tools.

The February *INSIGHT* leads off with "Sustainability: A Complex System Governance Perspective" by Charles Keating, Polinpapilinho Katina, Joseph Bradley, Richard Hodge, and James Pyne. The authors propose sustainability as a 'systems engineered product.' Two primary objectives are pursued. First, systems theory is used to provide an alternative view of sustainability. Second, a perspective of sustainability is developed through the paradigm of the emerging complex system governance field. The paper closes with the contributions, opportunities, and challenges for deployment of complex system govenance for enhanced development, transition, and maintenance of sustainable systems.

"Towards an Approach to Co-Execute System Models at the Enterprise Level" by Jovita Bankauskaite, Zilvinas Strolia, and Aurelijus Morkevicius studies Systems Modeling Language (SysML®) as the standard language to model systems, Unified Architecture Framework (UAF) as the framework, Unified Architecture Framework Modeling Language (UAFML) as the language to model enterprise architectures and proposes an approach for end-to-end co-execution of the integrated enterprise model. The challenge is not only how digital continuity can be maintained by connecting different layers of models (such as system models to system-of-systems models), but also how to perform detailed analysis and simulation at the enterprise level model.

"A Geo-Spatial Method for Calculating BEV Charging Inconvenience using Publicly Available Data" by Aaron Rabinowitz, John Smart, and Timothy Coburn address the operational inconveniences of recharging battery electric vehicles that significantly impact consumer decisions to buy or lease these vehicles. The authors present a method relating inconveniences to a small number of housing and local electric charging equipment infrastructure factors that enables quantitative analyses of policy effects for investment in battery charging infrastructure with the intent to reduce these operational inconveniences and thereby increase consumer demand for electric vehicles.

"Carbon Considerations for Systems Evolution" by David Flanigan and Kevin Robinson propose expanding the decision space in the early stages of system development to consider carbon expenditure to evaluate the solution space of alternatives in combination with performance, cost, risk, and schedule criteria. The authors develop and exercise the approach with a notional example.

"Model-Based Framework for Data and Knowledge-Driven Systems Architecting Demonstrated on a Hydrogen-Powered

Concept Aircraft" by Nils Kuelper, Thimo Bielsky, Jasmin Broehan, and Frank Thielecke present a a holistic framework for knowledge-based systems architecting using a model-based systems engineering approach. This framework conserves and provides knowledge to the engineer: information, data, and experiences about existing systems architectures, to the engineer. The framework is then demonstrated by conserving and reusing formalized knowledge for the design of a novel hydrogen-powered concept aircraft. On-board systems architecture models are saved in a database and automatically recreated reducing development time.

"Applying a System of Systems Perspective to Hyundai-Kia's Virtual Tire Development" by Sunkil Yun, Shashank Alai, Yongdae Kim, Jaehun Jo, Tae Kook Kim, Dahyeon Lee, Lokesh Gorantla and Michael Baloh presents a proof-of-concept that applies a top-down system of systems perspective to a virtual product development process to develop a performance-critical component of a vehicle, the tire, in response to growing environmental concerns as expressed by the United Nations Economic Commission for Europe. CO_2 emission regulations are driving the automobile industry to provide sustainable solutions. Automotive suppliers have been developing low rolling resistance tires as a practical solution to improving vehicle fuel efficiency and reducing emissions. The authors develop a consistent, layered, vehicle architecture model starting from the system of systems operational context down to the lowest level of system decomposition in the physical architecture thereby capturing top-down knowledge traceability. Using the concept of functional chains, several vehicle performance views are captured that serve as the basis for architecture verification orchestration across engineering domains using a cross-domain orchestration platform thereby validating key vehicle/tire performance metrics, that influence the tire design parameters.

"Think Like an Ecosystem: Transitioning Waste Streams to Value Streams" by Rae Lewark, Allison Lyle, Kristina Carroll, and Casey Medina note that linear production design disposes of resources before their optimal value have been realized and loses recyclable resources to waste streams. The economic infrastructure of the planet needs to be reimagined to meet human and ecological needs. The development and implementation of circular systems is key to the creation of sustainable global production. The authors illustrate considerations systems engineers can take to close the waste-resource gap using the analysis of copper used in medical devices. Developing wasteless design mimics the resiliency seen in ecosystems and accelerates the evolution of the global economy to meet the needs of companies, the environment, and humankind.

We hope you find *INSIGHT*, the practitioners' magazine for systems engineers, informative and relevant. Feedback from readers is critical to *INSIGHT*'s quality. We encourage letters to the editor at insight@incose.net. Please include "letter to the editor" in the subject line. *INSIGHT* also continues to solicit special features, standalone articles, book reviews, and op-eds. For information about *INSIGHT*, including upcoming issues, see https://www.incose.org/products-and-publications/periodicals#INSIGHT. For information about sponsoring *INSIGHT*, please contact the INCOSE marketing and communications director at marcom@incose.net. ■

INSIGHT Special Feature

Sustainability: A Complex System Governance Perspective

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■ ABSTRACT

This paper explores the sustainability field from a complex system governance (CSG) perspective. In general, sustainability suggests maintenance at a specific rate or level. It is also frequently held as maintaining ecological balance to negate the depletion of natural resources. CSG offers sustainability a theoretically grounded, model based, and methodologically sound approach to better inform sustainability design, execution, and development for complex systems. CSG examines sustainability as an outcome-based product resulting from effective governance of an underlying system which produces sustainability. Thus, sustainability is proposed as a 'systems engineered product', whose design, execution, and development will be favored by CSG systems engineering. Following an introduction, two primary objectives are pursued. First, systems theory is used to provide an alternative view of sustainability. Second, a perspective of sustainability is developed through the paradigm of the emerging CSG field. The paper closes with the contributions, opportunities, and challenges for deployment of CSG for enhanced development, transition, and maintenance of sustainable systems.

INTRODUCTION

The motivation for this paper is to enrich the sustainability body of knowledge for by introducing an alternative paradigm, complex system governance (CSG), as a theoretically grounded, model based, and methodologically sound approach to design, execute, and develop more sustainable systems. Sustainability is a concept that is in 'good currency', as society, and systems engineers, must continually grapple with the myriad of complex systems and their associated byproducts. At a most basic level, sustainability conveys that a system maintains a specific rate or level and embodies ecological balance to negate the depletion of natural resources. At a global level, the United Nations Brundtland Commission in 1987 defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." This remains in use today as the United Nations strives towards meeting its UN Sustainable Development Goals (UN 2022).

However, there are a multitude of perspectives, definitions, and themes that delineate 'sustainability'. In fact, as early as 2007, Johnston et al. (2007) placed the count of sustainability definitions in excess of 300 in the academic literature. The exponential rise of definitions continued as Young and Dhanda (2012) reported over 500 definitions of sustainability. Additionally, sustainability has been applied across a variety of specific fields and applications, such as Industry 4.0 (Ejsmont et al. 2020), supply chain management (Martínez-Jurado and Moyano-Fuentes 2014), manufacturing facilities (Chen et al. 2014), agriculture (Candemir, et al. 2021), corporations (Swarnapali 2017), education (Jeronen et al. 2016), and development (Paul 2008). In examination of sustainability, the essence of major themes of sustainability is captured in Table 1.

The literature and body of knowledge for sustainability is somewhat fragmented. As appealing as sustainability is on a conceptual level, it still suffers from being a very strong concept, but not particularly rigorous in technical formulation. This does not demean the works of sustainability. On the contrary, it suggests that there is room in the body of knowledge for new and novel approaches to achievement and maintenance of sustainability. Irrespective of the spread of the sustainability literature, there are several themes that serve to delineate the field. Table 1 provides a summary of key themes in sustainability and the significance for Systems Engineering.

Given this perspective of sustainability, systems engineering has several challenges. First, sustainability is something that should be considered and incorporated into the design of complex systems. The consideration of sustainability represents respectful and smart systems engineering. Second, sustainability is not free. While the long-term benefits are certainly desirable, sustainability, like any design 'illity,' carries associated costs. As always with design considerations, there are tradeoffs. Irrespective of how desirable design for

Table 1. *Major sustainability themes and significance for systems engineering (consolidated and amplified to systems engineering from Freyman's (2012) categories)*

Sustainability Theme	Significance for Systems Engineering
***Long View Focus* – emphasis on sustainability as a long-range future development focus versus a short term developmental perspective.**	Sustainability requires looking beyond the near term. Emphasis must be given to the long view required for design, execution, and evolution of systems such that they not only exist in the present, but also provide trajectory for the future. The sacrifice of long-term decisions for the expedience of short-term gains must be resisted to support sustainability in this and future generations.
***Holistic and Systems Based* – system understanding at the level of the autonomous whole, based in performance, behavior, or structure that is not attributable to 'parts' but rather 'interaction of parts.'**	Considerations of sustainability based in holism must reach beyond technical only based preoccupations. The entire impact spectrum of technology, social, human, managerial, organizational, economic, political, policy, and information must also be considered. SE for sustainability is challenged to 'open the aperture' of exploration to preclude overly narrow efforts by including the wider array of attributes that can influence design, analysis, and development of sustainable systems for the needs of future generations.
***Environmental, Social, Economic Considerations* – emphasis of multiple interrelated aspects of sustainability, beyond just an environmental focus.**	Sustainability is not restricted to a limited set of dimensions. Instead, a wider spectrum of considerations expands sustainability beyond narrowly focusing on only environmental concerns. While environmental aspects of sustainability are necessary, they are not sufficient to provide for sustainability. The entire range of social, economic, and environmental concerns, and their interrelationships, must be considered. At a social systems level, sustainability must avoid narrow mono-cultural outcome considerations through inclusion of perspectives from multiple cultures influencing the system.
Complexity – appreciation of the multiple variables, rich interrelationships, dynamic shifts, and emergence.	Complexity calls to question traditional forms of design, analysis, and transformation of systems. Complete prediction, control, explanation, and understanding of complex systems and their problems is a virtuous, but unattainable, pursuit. Instead, SE for sustainability must embrace the new realities of complexity and adjust models, methods, and tools to effectively engage this reality. Boulding's hierarchy of systems complexity reminds us never to accept as final a level of analysis below the level of complexity of the system of interest (Boulding, 1956).
***Carrying Capacity* – realization that there are limits to what sustainability can achieve within feasible boundaries.**	Irrespective of how diligent system design is engaged, there are limits to what can be achieved and maintained for sustainability. In effect, there is a carrying capacity beyond which sustainability cannot be achieved. This is critical to meter expectations as to what might be possible, even with the most diligent and effective application of SE to produce sustainable systems.
***Equity* – establishment of a sense of fairness in matters concerning the maintenance of long-term existence across environmental as well as other societal attributes**	Sustainability has implications for not only those individuals/entities that are direct owners, operators, developers, and maintainers of systems – but also those individuals/entities that impact, and are impacted by, sustainable systems. The impacts and sustainability of systems must take into account the notion of fairness in the establishment of societal benefits versus costs provided by sustainable systems. Natural resources must be metered and judiciously preserved for future generations – invoking generational fairness.

sustainability is, there are tradeoffs that must be made. Third, sustainability is not a limited effort. Sustainability is appropriate and must be factored into aspects of design, execution, maintenance, and evolution of a system over the entire life cycle. This also includes considerations for system disposal at the end of the system life cycle. Fourth, the sustainability field, and inclusion of sustainability for systems engineering, can be amplified by consideration of alternative paradigms that incorporate sustainability. CSG is one such alternative paradigm that can support a different viewpoint for sustainability.

Complex system governance (CSG) is an emerging field in the embryonic stages of development (Keating et al. 2022). CSG offers an emerging and untapped perspective for sustainability, focusing on 'governance' to steer a system to maintain balance in the long term. CSG offers sustainability a theoretically grounded, model based, and methodologically sound approach to deal with sustaining complex systems and enhanced effectiveness in dealing with their problems – all in the midst of hyper turbulent environments and internal system flux. The CSG perspective suggests sustainability as an outcome-based product resulting from the consistent and values-based performance of governance functions. Thus, sustainability is examined as a 'systems engineered product' of an underlying system, whose design, execution, and development will be favored by CSG systems engineering. Following this introduction, this paper pursues two primary objectives. First, systems theory is used to provide an alternative view of sustainability. This view is focused on the implications of systems theory propositions (laws, concepts, and principles) that serve to explain the structure, behavior, and performance of complex systems (Whitney et al. 2015) for the establishment and maintenance of sustainability. Second, a perspective of sustainability is developed through the paradigm of the emerging CSG field. CSG fundamentals, including functions and communication channels, are examined with respect to sustainability as a 'systems engineered product'. The paper concludes with the contributions, opportunities, and challenges for deployment of CSG for enhanced development, transition, and maintenance of sustainable systems.

A SYSTEMS THEORY PERSPECTIVE FOR SUSTAINABILITY

Examinations of systems theory (ST) find their roots emanating from general systems theory (GST). There is no commonly accepted and ubiquitous definition of GST. However, the origins of GST can be traced to the 1940s as an attempt to provide a break from the traditions of *reductionism*. *Reductionism* is rooted in the successive 'breaking apart' of a system to produce understanding that is held in the parts of a system. Thus, *reductionism* is closely aligned with the scientific method, and holds that a complex organism is understood as the sum of its parts, and therefore system understanding can be attained from the properties of constituent elements (Hammond 2010 and von Bertalanffy 1968).

Laszlo (1969), providing an alternative to reductionism, suggested that GST is related to ideas of 'wholes'. These wholes have having irreducible properties, are embedded in an environment, are subject to centralization, engage in self-organization of structure and configuration, and exhibit holarchy as the interaction of autonomous elements. Fundamentally, these systems ideas suggest organization/structure among constituents, relations among constituents, and the inherent interactions between constituents (von Bertalanffy 1972). Additionally, the applicability of GST spans both different 'types' of system as well as finding commonality across different systems, disciplines (for example, systems engineering) and sectors within which they exist and serve. Thus, GST provides a foundation from which our understanding of systems could be universally leveraged to enhance our understanding of the 'systems driven' world and its problems. Although the original aims of GST have not yet been fully realized, the work continues with attempts to develop more 'universally' applicable theoretical formulations of systems.

Systems theory (ST) provides a robust conceptual foundation that, projecting to CSG, can influence design, execution, and development of sustainability for complex systems. Based on the articulation of systems theory by (Adams et al. 2014; Whitney et al. 2015; Keating et al. 2020; Keating et al. 2016), at a basic level systems theory can be understood as a set of *axioms* (truths about systems that are accepted without need for justification) and *propositions* (a collected set of principles, concepts, and laws serving to explain structure, behavior, and performance of systems and their phenomena). ST suggests several central tenets concerning the capacity to deal with environments marked by increasing complexity, instabilities, and ambiguity – all of which are impacts on system sustainability. Among these themes we include:

1. System behavior, structure, and performance result from the interactions among the system elements/entities.
2. Holism invokes understanding at the level of the 'whole system' which cannot be deduced from the individual elements/entities – system level properties, behavior, and performance emerge from interactions between system elements.
3. As mentioned above, ST consist of the set of axioms and propositions that offer explanation for system behavior and performance.
4. Without exception, all systems are subject to the axioms and propositions which constitute ST.

Adams, et al. (2014) organized the fragmented body of knowledge for systems theory into a set of 7 axioms and 30 associated propositions. While the complete articulation of this set is beyond the scope of this paper, below we have constructed a table with several key ST propositions and their implications for sustainability. This table is drawn from the works of Adams et al. (2014), Whitney et al. (2015), Keating et al. (2016), and Castelle et al. (2022). Readers are referred to these works for a deeper examination of the propositions.

Based on ST, there are significant implications for expanding our understanding of sustainability. Table 2 provides several ST propositions and the SE for sustainability implications of those propositions. The third column (systems engineering for sustainability implications) extends the propositions for the current exploration of sustainability.

From this set of definitions/perspectives, and other literature on ST, there are three central themes to be developed in relationship to sustainability.

(1) *System Viability* – Beer (1979) introduced viability as the ability of a system to continue existence. The maintenance of viability is required for a system to be sustainable in the long term. It is important that viability is not a 'binary,' either/or proposition, that would suggest a system exist or does not exist. Instead, system viability exists over a range of existence. At the high end, viability would indicate that a system is performing at a high level. At the low end, viability would be limited and only support a minimal existence. Thus, sustainability can be thought of as existing along a range of viability.

Requisite Variety – Requisite variety, following the development by Ashby (1956, 1991), requires that a system be capable of matching or exceed the variety (for example, disturbances) being generated by the environment. Variety in the environment can be thought of as the number of states that exist in the environment and might act to challenge or disturb a system. Sufficiently matching the variety of a system's relevant environment is essential to maintain existence (viability) and sustainability for the system over time. This is particularly important as the environment will continue to evolve and generate variety which must be matched by the system's regulatory capacity to maintain sustainability.

(2) *Variety Engineering* – Concerned with the purposeful design, execution, and develop of systems to provide the regulatory capacity essential to match environmentally generated variety, as well as variety generated internal to a system. If variety is not effectively absorbed, the ability of a system to remain viable can be called into question. Thus, establishment of requisite variety is essential to viability and sustainability of systems. The engineering of variety provides the essence of maintaining viability and, for sustainability, provides for long-term continuing existence by regulating variety.

We now turn our focus to the CSG paradigm and its contributions to sustainability.

THE CSG PARADIGM AND SUSTAINABILITY

CSG has been formally defined as the "*Design, execution, and evolution of the metasystem functions necessary to provide control, communication, coordination, and integration of a complex system*." (Keating 2015, p. 274). This definition of CSG suggests several synthesizing themes based on the prior works of Keating and Katina (2019) and Keating et al. (2022).

(1) *Design* focuses on purposeful engagement in the creation, deployment, and maintenance of the governance system. Design must focus on engineering of variety in a complex system such that the regulatory capacity matches the external and internal variety for the system.

(2) *Execution* is the active initiation of the design. Execution compensates for areas that the design is insufficient to address variety. In effect, execution is responsible for compensating for unabsorbed variety originating internally or externally to the system.

Table 2. (Some) Systems theory propositions for sustainability

Proposition	Explanation	SE for Sustainability Implications
Communication (Shannon 1948a, 1948b; Skyttner 2005)	Communication is a transaction which occurs between the information source and the destination. The aim is the generation and reproduction of the transmission.	Communication is critical to sustainability. Sustainability is dependent on the flow (transmission of information within the system) and interpretation (actionable information which supports consistency in understanding).
Control (Checkland 1993)	The process through which an entity (whole) retains its identity and/or performance under changing conditions and circumstances.	Control requires establishment of regulatory capacity and constraints in systems design and execution. System control is essential to ensure continuing sustainability of systems.
Emergence (Checkland 1993; Aristotle 2002)	Whole entities exhibit properties and patterns that are meaningful only when they are attributed to the whole, not its parts.	Emergence results in patterns, behavior, or performance in systems resulting from their operation. This cannot be predicted in advance. Sustainability, and activities to achieve sustainability, are subject to emergence.
Complementarity (Bohr 1928)	Two different perspectives or models about a system will reveal truths regarding the system that are neither entirely independent nor entirely compatible.	Multiple different viewpoints and perspectives should be considered for complex system sustainability. There is always a logic and corresponding set of assumptions that make alternative viewpoints correct. Sustainability can be enhanced by understanding and challenging divergent logic/assumptions and potentially reducing unnecessary conflict.
Incompressibility (Cilliers 1998; Richardson 2004)	There is no element of a system that has complete knowledge of the system. There is always incompleteness in the ability to fully comprehend a system. Thus, the best representation of a complex system would be the system itself. Any representation other than the system itself will lack in completeness of understanding.	Any representation (model) of a complex system is based on abstractions, inevitably subject to abstraction error. Thus, development of sustainability, based on models, is enhanced by accepting that system knowledge is always incomplete, subject to interpretation, and fallible. System knowledge must be continually questioned for appropriateness, and we must be willing to evolve formulations based on new knowledge and interpretations.
Holism (Smuts 1926)	Systems must be considered as a whole, which will exhibit structure, behavior, or performance not attributable to the individual or collective parts. Instead, the behavior results from the interrelationships between parts.	Design and achievement of sustainability is subject to the entire spectrum of influences, including: technology, social, human, economic, organizational, managerial, policy, and political dimensions. Narrow conceptions of sustainability can and should be challenged across the holistic spectrum and associated interactions.
Boundary (von Bertalanffy 1968; Skyttner 2005)	The abstract, semi-permeable perimeter of a system separates the system from everything that exist external from the system. Boundary conditions may prevent or permit entry of matter, energy or information for the system.	Ultimately, boundaries determine what is included/excluded for sustainability efforts and should be made explicit through criteria for inclusion/exclusion concerning the system of interest. Additionally, sustainability boundaries can change over time with new knowledge and resolution of ambiguities.
Minimal critical specification (Cherns 1976, 1987)	This principle has two aspects, negative and positive. The negative implies that no more should be specified than is absolutely essential; the positive requires that we identify what is essential.	Excessive constraint for system regulation reduces autonomy and can be wasteful of scarce system resources. In pursuit of sustainability, care must be taken to only minimally constrain a system, providing only those constraints that are necessary to preserve desired outputs and outcomes.
Requisite saliency (Boulding 1966)	The factors that will be considered in a system design are seldom of equal importance. Instead, there is an underlying logic awaiting discovery in each system design that will reveal the significance of these factors.	The characteristics (e.g., design parameters for sustainability) are never of equivalent importance. Sustainability should provide clarity for the different weightings and priorities of different factors or attributes. This will provide more congruent trade-off decisions with respect to sustainability throughout the system lifecycle.
Equifinality (von Bertalanffy 1950)	If a steady state is reached in an open system, it is independent of the initial conditions and determined by the system parameters, e.g., rates of reaction and transport.	SE practice related to sustainability must accept that there are alternative approaches (pathways and means) that can produce equivalent sustainability results. It is naïve to think that sustainability can only be achieved through one 'optimal' approach.

Table 2. (Some) Systems theory propositions for sustainability (continued)

Proposition	Explanation	SE for Sustainability Implications
Satisficing (Simon 1955, 1956)	The decision-making process that results in selection of an 'acceptable 'alternative. While this alternative might not be the best (optimal), it is nevertheless adequate for the present circumstances.	SE practices for sustainability must accept that, for complex systems, 'optimal' is not achievable. There are multiple different possibilities that can achieve desirable sustainability performance. Pursuit of optimal sustainability outcomes or design consumes scarce resources that can be expended in pursuit of other sustainability pursuits.
Redundancy of Potential Command (McCulloch 1965)	Effective action is achieved by an adequate concatenation of information.	For sustainable systems, decision authority should reside at the point where decision/action can best be taken in response to emergent issues. This is the point where decisions can become actionable. The farther decisions are removed in time, location, and action, the greater the possibility for reduced effectiveness.
Dynamic Equilibrium (von Bertalanffy 1968; Miller 1978)	An entity continues to exist as it undergoes different fluxes and variabilities in flows of matter, energy, and information – this produces an equilibrium that is not static and shifting over time.	Sustainable systems must be capable of adjusting 'on the fly' to changing circumstances and conditions. This is necessary to maintain stability in the face of inevitable flux in systems and environments.
Homeorhesis (Waddington 1957, 1968)	The maintenance of trajectory in dynamic systems by continual adjustments. These adjustments provide regulation, via interrelated mechanisms, to produce dynamic equilibrium.	Achievement of sustainability requires constant adjustment to maintain the desired trajectory of the system. As inevitable changes in external circumstances occur, they will require that adjustments be made. Sustainability trajectory adjustments are best achieved through purposeful means rather than response to chance or crisis events.
Homeostasis (Cannon 1929)	Regulation of a systems internal environment such that a set of variables are kept within limits necessary to dynamically maintain system integrity.	Sustainable designs must provide adjustments to assure that key (internal) parameters maintain balance in response to inevitable internal flux that might impact ability to achieve sustainability objectives.
Redundancy (Pahl et al. 2011)	Means of increasing the reliability of a system by providing excess resources or capacity beyond those that are minimally required to achieve system performance.	Sustainability must provide for the necessary mechanisms that permit allocation of resources necessary to support sustainability goals. Challenges to sustainability cannot be precisely known in advance. Therefore, it is prudent to have an excess of resources available to compensate as necessary to maintain sustainability, even under difficult circumstances and inevitable variabilities, whose specific form cannot be known in advance.
Self-organization (Ashby 1947)	The emergence of patterns of interaction, defining system structure, without regulation or constraints being imposed on the system.	Self-organization permits patterns to emerge without interference (constraint) being invoked. For achievement of sustainability in SE, Self-organization requires the least energy for organization of patterns and system structure. It is an effective approach for design, if sustainability performance objectives continue to be at desirable levels.
Sub-optimization (Hitch 1953)	If each subsystem, regarded separately, is made to operate with maximum efficiency, the system as a whole will not operate with utmost efficiency.	Integration of system elements to achieve and maintain sustainability requires those elements surrender some level of autonomy in favor of system integration. Sustainability should, by design, achieve a balance between subsystem autonomy and system integration.
Requisite Hierarchy (Aulin Ahmavaara 1979)	The weaker in average are the regulatory abilities and the larger the uncertainties of available regulators, the more hierarchy is needed in the organization of regulation and control to attain the same result, if possible, at all.	Those responsible for system sustainability should 'flatten' the hierarchy. This should focus on regulatory capacity being provided to assure consistent performance. Care must be taken to ensure that only the essential hierarchy necessary to maintain control of a system is put into place.
Requisite Variety (Ashby 1956)	Control can be obtained only if the variety of the controller is at least as great as the variety of the situation to be controlled.	SE practice for sustainability must ensure that the regulatory capacity and mechanisms are sufficiently matched to that required by the environment. Lacking sufficient 'matching' variety will eventually overwhelm a system and threaten sustainability.

Table 3. Nine metasystem functions summary (based on work of Keating et al. 2014, 2016, 2019, 2022)

Metasystem Function	Description
Metasystem Five (M5) – Policy and Identity	Focused on overall steering and trajectory for the system. Maintains identity and balance between current and future focus.
Metasystem Five Star (M5*) – System Context	Focused on the specific context within which the metasystem is embedded. Context is the set of circumstances, factors, conditions, or patterns that enable or constrain execution of the system.
Metasystem Five Prime (M5') Strategic Performance	Provides oversight of the system performance indicators at a strategic level, identifying performance that exceeds or fails to meet established expectations.
Metasystem Four (M4) – System Development	Maintains the models of the current and future system, concentrating on the long-range development of the system to ensure future viability.
Metasystem Four Star (M4*) – Learning and Transformation	Focused on facilitation of learning based on detection and correction of design errors in the metasystem functions and planning for transformation of the metasystem as well as the systems being governed by the metasystem.
Metasystem Four Prime (M4') – Environmental Scanning	Designs, deploys, monitors, and processes sensing of the environment for trends, patterns, or events with implications for both present and future system viability. Maintains the model of the system environment.
Metasystem Three (M3) – System Operations	Focused on the day-to-day execution of the metasystem to ensure that the overall system maintains established performance levels.
Metasystem Three Star (M3*) – Operational Performance	Monitors system operational performance to identify and assess aberrant conditions, exceeded performance thresholds, or anomalies.
Metasystem Two (M2) – Information and Communications	Designs, establishes, and maintains the flow of information and consistent interpretation of exchanges (through communication channels) necessary to execute metasystem functions.

(3) *Evolution* recognizes that systems must and will change over time. *Evolution* by its very nature suggests that this change is focused on maintaining sustainability over the long term. There is a precarious balance between long term sustainability and short-term survivability of a system. This requires a purposeful balance, without sacrifice of the long- or short-term system performance. This ensures that the system remains viable (continues to exist) in both the short-term present operation as well as the long-term future for the system.

(4) *Control* establishes constraints necessary to ensure consistent performance and future system trajectory. This provides the regulatory capacity necessary for sustainability in the long term and maintenance of viability in the short term. In short, control ensures that a system continues to produce desirable performance by balancing the tension between autonomy and integration.

(5) *Communications* provides for not only the flow of information, but also the interpretation of that information. In this sense, consistency in decision, action, and interpretation are supported throughout the system by effective communications.

(6) *Coordination* provides for effective interaction between system elements to prevent unnecessary instabilities within and external to the system. If sustainability is to be pursued, achieved, and maintained, integration is necessary to maintain system unity through common purpose, designed accountability, and maintenance of balance within the system and between the system and its environment.

(7) *Metasystem functions* – There are 9 metasystem functions that must be performed by all complex systems to maintain viability (existence). These functions are derived and extended from Beer's metasystem concept in the viable system model (1979, 1981, 1985). These functions support the long-term sustainability of a system under conditions of internal flux and external (environmental) turbulence. The evaluation of these functions provides a basis for sustainability design and maintenance.

(8) *Communication Channels* – There are 10 communication channels that provide for flow and interpretation of information within a complex system in the CSG framework. These channels may be performed by formal/informal, tacit/explicit, or effective/ineffective mechanisms that serve to support achievement of the channel purpose.

The metasystem functions operate in conjunction with 10 communication channels, which provide for the flow and interpretation of information with the system of interest. Table 4 provides a brief overview of the 10 communication channels and the functions to which they are associated.

The CSG paradigm (Figure 1) can be succinctly stated as:

> *System viability is maintained through performance of essential governance functions and communication channels by mechanisms, subject to fundamental systems theory propositions.*

The following elaboration of the CSG paradigm is a short summary of the existing research, instruction, and practice materials. There are six essential points of CSG, included in Keating et al. (2022) which are expanded here to highlight their implications for sustainability:

1. *All systems are subject the principles, laws, and concepts of systems theory, without exception*. Similar to the accepted laws of natural science (for example, gravity), systems also have laws (propositions) that govern their existence and behavior.

   Sustainability of systems is beholden to these propositions. System propositions are always

Table 4. Summary of the CSG communication channels (based on Katina and Keating (2019)).

Channel and Responsibility	CSG Metasystem Role
Command (Metasystem 5)	• Provides non-negotiable direction to the metasystem and governed systems/entities • Primarily from Metasystem 5 and disseminated throughout the system
Resource bargain/ Accountability (Metasystem 3)	• Determines and allocates the resources (manpower, material, money, methods, time, information, support) to governed systems/entities • Defines performance levels, responsibilities, and accountability for governed systems • Primarily an interface between Metasystem 3 to the governed systems/entities
Operations (Metasystem 3)	• Provides for the routine interface focused on near term operations • Concentrated on direction for system production (products, services, processes, information) consumed external to the system • Primarily an interface between Metasystem 3 and governed systems
Coordination (Metasystem 2)	• Provides information for metasystem and governed systems balance and stability • Ensures that information concerning decisions and actions necessary to prevent disturbances are shared within the metasystem and governed systems/entities • Primarily a channel designed and executed by Metasystem 2
Audit (Metasystem 3*)	• Provides routine and sporadic feedback concerning operational performance • Investigation and reporting on problematic performance issues within the system • Primarily a Metasystem 3* channel for communicating between Metasystem 3 and governed systems concerning performance issues
Algedonic (Metasystem 5)	• Provides a 'bypass' of all channels when the integrity of the system is threatened • Compels instant alert to crisis or potentially catastrophic situations for the system • Directed to Metasystem 5 from anywhere in the metasystem or governed systems/ entities
Environmental Scanning (Metasystem 4')	• Provides design for sensing of the external environment • Identifies environmental patterns, trends, activities, or events with system implications • Primarily from Metasystem 4' and disseminated throughout the system
Dialog (Metasystem 5')	• Provides for consistency in system decisions, actions, and interpretations congruent with system purpose and identity • Provided to Metasystem 5' from anywhere in the metasystem or governed systems/ entities
Learning (Metasystem 4*)	• Facilitates detection and correction of error within the metasystem as well as governed systems, focused on system design issues as opposed to execution issues • Directed to Metasystem 4* from anywhere in the metasystem or governed systems/ entities
Informing (Metasystem 2)	• Provides for flow and access to routine information in the metasystem or between the metasystem and governed systems/entities • Primarily a Metasystem 2 channel to disseminate information throughout the system

there, non-negotiable, unbiased, and explain system performance as well as impacts on future system sustainability. Systems engineering practitioners concerned with sustainability must ask, 'do we understand systems propositions and their impact on system design, execution, and development for future system sustainability?' For example, overdependence on self-organization (allowing structure and behavior to evolve without constraint) for evolving sustainable systems is not likely to produce the level of system sustainability performance desired. Balancing self-organization with purposeful design is essential to provide sustainability.

2. *All systems perform essential governance functions that determine system performance.* Nine system governance functions are performed by all systems, regardless of sector, size, or purpose. These functions define 'what' must be achieved for governance of a system. Every system invokes a set of unique implementing mechanisms (means of achieving governance functions) that determine 'how' governance functions are accomplished. Mechanisms can be formal-informal, tacit-explicit, routine-sporadic, or limited-comprehensive in nature.

Sustainability of systems can be viewed from the prism of governance functions that influence system continuity. Systems engineering practitioners concerned with sustainability must ask, 'can we articulate the governance functions for our system of interest and assess the enabling/ constraining impacts on future system sustainability?'. For example, an

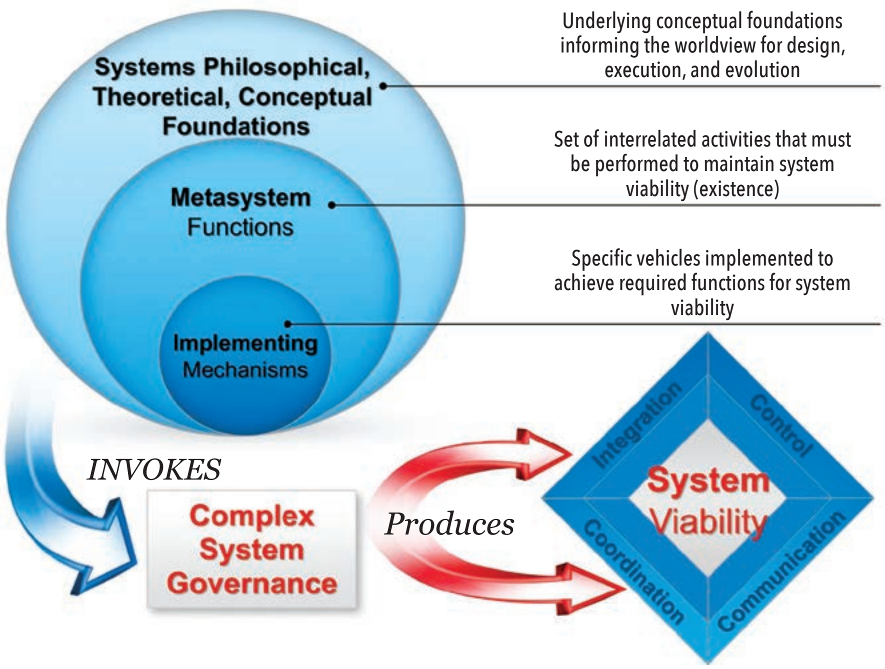

Figure 1. The CSG paradigm (Keating et al. 2022)

imbalance in focus between present system 'sustainability' and future system 'sustainability' can result in sacrifice of the system in either the long term, short term, or both.

3. *The execution of CSG functions generates the communication, control, coordination, and integration responsible for producing system performance*. *Control* invokes the constraints which provide the regulatory capacity of a system. These constraints should be at a minimal level while still achieving desired system performance. Thus, autonomy (freedom and independence of decision/action/interpretation) of system constituents is preserved to the greatest degree possible. *Communications* provides for the consistent flow and interpretation of information. It supports congruence in decisions, actions, and interpretation. *Coordination* ensures that there is not excessive oscillation within the system. Unnecessary and unproductive fluctuations are avoided through standardization, protocols, and procedures. *Integration* is focused on the achievement and maintenance of system identity. This assures that the system is a 'unity,' acting and performing as a whole, beyond that capable by individual system constituents.

   Systems engineering practitioners concerned with sustainability must ask, 'do we understand system performance influences of control, communications, coordination, and integration (CCCI) in relationship to achievement of sustainability?' For example, permitting CCCI for systems to advance without purposeful development from a holistic view is not likely to produce the level of performance desired to gain and maintain sustainable systems.

4. *Execution of CSG functions, supported by associated communication channels, in accordance with system propositions, is responsible for the level of system performance achieved and continuing system viability.* Since all viable systems perform governance functions, the degree to which the functions are effectively performed will determine the performance of the system and continuing viability, which supports sustainability. Purposeful governance invokes a higher state of viability (existence) and can support enhanced system sustainability.

   Sustainability objectives are designed, executed, and evolved through governance functions. Systems engineering practitioners concerned with sustainability must ask, 'do we understand sustainability objectives within the governance functions such that their achievement will be ensured?' For example, all complex systems perform governance functions and communication channels, irrespective as to whether or not they are acknowledged. Acknowledgement of the functions and channels, coupled with their active development, provides a substantial step forward in propagating sustainable systems.

5. *There are performance consequences for violation of systems theory propositions in execution of governance functions.* Regardless of knowingly, or unknowingly, violating system propositions there will be consequences. This will ultimately impact the level of sustainability achieved and maintained for a system. In the best case, violations can result in degraded performance and hinder achievement of sustainability. In the worst case, violation can escalate to cause catastrophic consequences, even eventual system collapse, or outright failure to achieve sustainable systems.

   Systems engineering practitioners concerned with sustainability must ask, 'can we identify and trace sustainable system performance variabilities in relationship to violations of Systems Theory propositions?'. For example, understanding the violation of a system proposition, such as control (provision of constraint necessary to maintain system performance), will serve to provide a more informed view for maintenance of sustainable systems in the face of internal flux and external turbulence.

6. *Purposeful development of CSG functions can be instrumental in achieving higher levels of system performance.* Poorly performing systems should be examined for deficiencies in either governance functions or their supporting communication channels. This level of system investigation can reveal a deeper understanding of the 'systemic' sources of deficiencies, particularly with respect to support for sustainability. In many cases, tracing deficiencies to underlying governance function issues and violations of system propositions might offer alternative paths forward for prioritizing and targeting system improvements. Thus, purposeful system development can be supportive of a more rigorous, informed, and actionable approach to support system sustainability. Systems engineering practitioners concerned with sustainability must ask, 'are governance functions being purposefully designed, executed, and

developed to support future system sustainability?' For example, although sustainability has been extensively written about, there has not been a significant movement to appreciate the insights that can accrue from the purposeful assessment of governance functions, their interrelationship, and the impact their holistic development might have for acceleration and advancement of sustainable systems.

The preceeding six points explain the CSG paradigm and project the paradigm to sustainability.

CONCLUSION

For future systems engineering efforts concerned with inculcating sustainability into complex systems, CSG offers an approach that can make three major contributions. First, while sustainability can be somewhat nebulous, CSG provides a *rigorous formulation*, based in systems theory, that can add significant rigor for achievement of sustainability objectives for a system of interest. Second, the establishment of 'viability' through system design, execution, and development offers a *grounding for sustainability* that is currently not a part of the sustainability body of knowledge. This is not to disparage the significant and essential work that has been completed, is ongoing, and projected for the future of sustainability. On the contrary, CSG adds to the sustainability dialog with a model based, theoretically grounded, and paradigm driven approach to achievement of viable systems that can meet sustainability objectives by design. Third, CSG offers a *holistic view of sustainability*. This view cuts across the holistic spectrum of systems, including technology, social, economic, and political/policy dimensions that are each critical to the design, achievement, and maintenance of sustainable systems.

CSG does not offer a panacea for achieving and maintaining sustainable systems. However, it does offer engagement in a dialog that is presently absent in the sustainability literature. In addition, systems engineering will be challenged in the future to produce sustainable systems, appreciative of achieving long term balance and preservation of resources. CSG provides an approach to better meet these future challenges. ■

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Towards an Approach to Co-Execute System Models at the Enterprise Level

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ABSTRACT
Industry 4.0, the Internet of Things, and large-scale system-to-system interactions are driving digital transformation in the industry. Model-based systems engineering (MBSE) is one of the core paradigms behind this transformation. MBSE practices are widely applied to enterprise (including system of systems and mission) architectures, which become a crucial part of successful digital transformation. The core challenge today is not only how digital continuity can be maintained by connecting different layers of models (such as system models to system-of-systems models), but also how to perform detailed analysis and simulation at the enterprise level model. This paper studies Systems Modeling Language (SysML®) as the standard language to model systems, Unified Architecture Framework (UAF) as the framework, Unified Architecture Framework Modeling Language (UAFML) as the language to model enterprise architectures and proposes an approach for end-to-end co-execution of the integrated enterprise model.

INTRODUCTION

Enterprise is defined as *a purposeful or industrious undertaking (especially one that requires effort or boldness)* (Wordnet). Enterprise Architecture is about managing and developing architecture of enterprise, system, or system-of-systems (SoS) (Morkevicius, Bisikirskiene, and Bleakley 2017). (Jamshidi 2009) defines an SoS as an integration of a finite number of constituent systems which are independent and operatable, and which are networked together for a period of time to achieve a certain higher goal. Maier (1998) characterizes SoS applications as having five traits: operational independence, managerial independence, independent evolutionary development, emergent behaviors, and geographic distribution.

Standards, including UAF® (OMG 2022), emerged as a new way to capture knowledge of the enterprise. UAF has ways of managing SoS development in all of these areas, as described by Maier (1998). The Unified Architecture Framework has become a prominent upgrade within the US Department of Defense (DoD), North Atlantic Treaty Organization (NATO), and commercial organizations. UAF architecture models make it possible to develop an understanding of the complex relationships existing between organizations, systems, and software, and enable analysis of these relationships combined.

The UAF operational domain captures the logical architecture of the enterprise (including requirements, operational behavior, structure, and exchanges) required to support capabilities, whereas the UAF resources domain captures resource configurations and how they implement the operational requirements and serve in the overall achievement of capabilities. UAF, however, does not specify ways and means to define an architecture for a single resource, such as a system. Systems Modeling Language (SysML) (OMG 2019) is the standard for defining systems architecture. However, SysML is neither a framework nor a method. It provides no information about the modeling method and thus must be combined with some methodology to become truly applicable. For this reason, we found the MagicGrid® (previously known as MBSEGrid) methodology defined in (Mazeika, Morkevicius, and Aleksandraviciene 2016), (Morkevicius et al. 2017b), (Morkevicius et al. 2020), as the fit for purpose to our research.

Though integrating SysML to UAFML at the level of language metamodels is not the primary goal of this paper and it has been already defined in Morkevicius, Aleksandraviciene, and Krisciuniene (2021), it is important to highlight the relationship between different layers of frameworks. Figure 1 depicts the levels of abstractions of UAF and MagicGrid and how one corresponds to the other in order to have a smooth transition between the two frameworks.

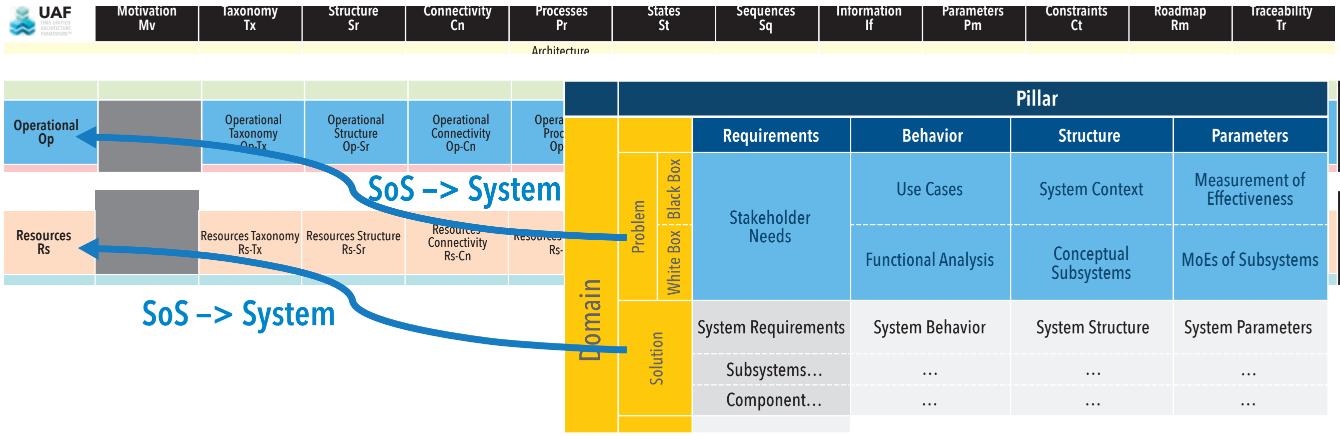


Figure 1. Alignment between levels of abstraction of UAF and MagicGrid

The UAF operational viewpoint is the same level of abstraction as a problem domain in MagicGrid and the UAF resources viewpoint is the same level of abstraction as the MagicGrid solution domain. The difference is that UAF defines the interaction of different types of resources in the SoS scenario and MagicGrid defines the architecture of the system taking part in that scenario. Understanding this relationship, we can connect different system models in the UAF resources viewpoint and co-execute them; that is, we execute the resource configuration. This leads us to the goal of this paper, which is to provide guidelines for co-executing system models defined in SysML in the integrated model of UAF resource configuration.

This paper is structured as follows: in Section 2, related works are analyzed; in Section 3, the proposed approach is presented; in Section 4, application of the proposed approach is described; in Section 5, achieved results, conclusions, and future work directions are indicated.

RELATED WORKS

The use of simulation at the system engineering level is a common practice that is widely used in the systems engineering community. Many studies have been published that share knowledge and experience in the application of simulation techniques in the analysis of various systems engineering domains. Lin et al. (2015) presents an analysis of the baggage handling system at Taoyuan International Airport in Taiwan. Kotronis et al. (2016) describes how to apply simulation to SysML models that describe a rail transport system. Bankauskaite, Strolia, and Morkevicius (2021) presents the use of simulation in a trade study of an automatic transmission system. Furthermore, many researchers have developed and introduced new methods to analyze systems using simulation in conjunction with the SysML model. Abdulhameed, Alkindy, and Al-Mahdawi (2022); Morkevicius and Jankevicius (2015); and Messaoud, Hammad, and Loualalen (2017) proposed new simulation approaches to perform verification and validation analyses of the system architecture. Kotronis et al. (2022); Stella de Biase, Marrone, and Palladino (2022); and Jagla et al. (2021) provided new approaches that allow conducting a cost, impact, or safety analysis of the system architecture.

Simulation techniques are also relevant and feasible when referring to the system of systems engineering (SoSE) level. As SoSE models are complex, simulation facilitates the evaluation of SoS models and allows the various required analyses to be performed automatically. Many studies have been published introducing new methods for verifying and validating SoS. Park et al. (2020) presents a tool for simulation-based verification and analysis of SoS, called SIMVA-SoS. Honour (2013) discusses the main issues encountered when applying verification and validation methods to SoS. This paper also outlines some solutions to these issues. Ding, Wang, and Cao (2020) provides the verification method for UAF models based on description logic. Automated reasoning engines based on Tableau algorithms are used to verify UAF models based on precise semantics. Wang et al. (2017) proposes a method for modeling and verifying high-level SoS quality requirements. In addition, there are a number of published studies that provide methods and techniques for analyzing SoS models. Yan et al. (2014) proposes a new ontology-based method that is used to comprehensively evaluate the capabilities of SoS through simulation. Pan, Yin, and Hu (2011) introduces an integrated framework for SoS modeling and simulation methods that is based on the US Department of Defense Architecture Framework (DoDAF). SoS modeling and simulation methods are used to analyze the SoS architecture framework, identify weak links, and determine the direction and objective of SoS research and development. Bankauskaite, Morkevicius, and Butleris (2020) presents the validation rules for the initial assessment of the UAF architecture evaluation. Bankauskaite, Morkevicius, and Butleris (2021) introduces a new method of assessing SoS architectures through a trade study process.

However, the above-mentioned simulation usages are used only at one engineering level, either systems engineering or SoSE. There is a lack of methods that would assist engineers in combining systems engineering and SoSE for simulation purposes. Nevertheless, a recently published paper (Morkevicius, Aleksandraviciene, and Krisciuniene 2021) proposed an approach for transitioning from SoS to systems architecture. The proposed approach is standard-based, as it is based on the concepts of SysML, UAF, and UAFML. Although, the approach is not specifically related to simulation, but serves as a starting point for combining SoS and system levels for the use of simulation.

AN APPROACH TO CO-EXECUTE SYSML SYSTEM MODELS IN AN INTEGRATED UAF RESOURCE CONFIGURATION

The proposed approach provides guidelines for co-executing system models in SysML in the integrated UAF resource configuration. To enable various analyses at the UAF SoS level along with a more precise SysML model, it is necessary to connect the SysML system models in terms of UAF resource configuration. The introduced approach is divided into three levels of projects: SoS, system, and analysis. Each level provides the required guidance on transitioning from SoS to system architecture that enables co-execution of SysML system models in an integrated UAF resource configuration environment.

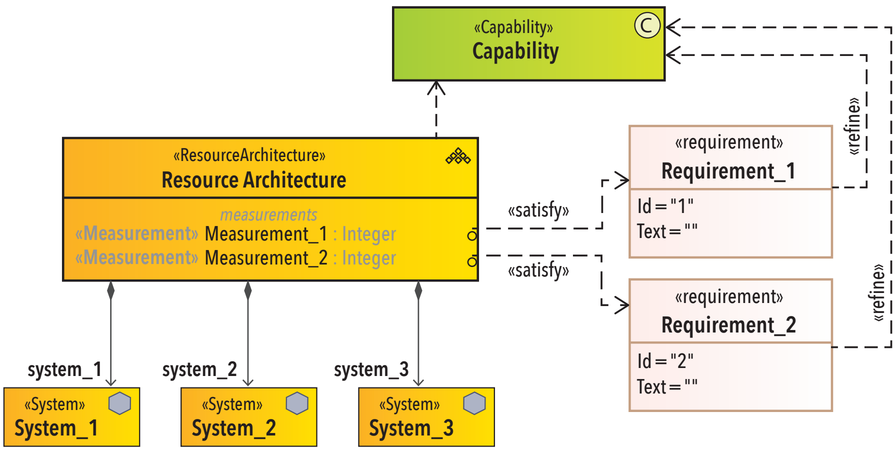


Figure 2. *SoS architecture taxonomy along with capabilities and requirements*

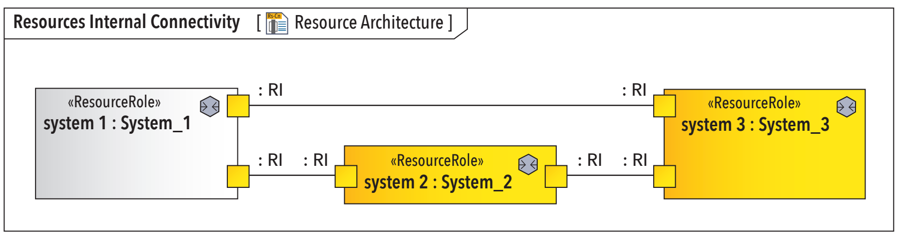


Figure 3. *Resources internal connectivity model*

SoS Level Project/UAF Resource Configuration

The UAF resources viewpoint captures the interaction of different resources, including human resources and systems, to meet operational requirements and achieve capabilities (see Figure 2). Resource exhibits the capability to determine that it realizes the ability of the enterprise to achieve the desired effect. At the SoS level, capabilities can be detailed by refining them with requirements, for example, to provide a quantified constraint that applies to the whole or part of the SoS architecture. Requirements that refine capabilities should satisfy measurable properties of resources that are typically used to support analysis, such as requirements verification, measure of effectiveness (MoE), etc.

However, the SoS level refers to a high level of the enterprise architecture and, typically, for certain analyses, this level lacks the details that are defined at a lower system level. In this case, it is necessary to co-execute SysML system models in an integrated UAF resource configuration to perform analysis at the SoS level with the required level of detail. The resources internal connectivity viewpoint (see Figure 3), which captures the interaction between internal resources, shows the intended UAF resource (colored in gray) that would need to be redefined with a more precise SysML system model.

System Level Project (MagicGrid)/SysML System Model

The next level is the system level that captures the architecture of a single system of interest (SoI). SysML as a language and MagicGrid as a method for developing system models using SysML cover two of the three main components of MBSE that enable the definition of system architecture.

The initial determination of the system context of the SoI occurs in the SoS level project, specifically through the resources connectivity viewpoint (Figure 3). MagicGrid captures the problem domain model of the SoI system context as a SysML block (Figure 4, first step). To connect the UAF and SysML models, a generalization is established from the SysML problem domain to the UAF operational performer (Figure 4, second step). This results in the SysML problem domain block becoming a subtype of the UAF operational performer and inheriting all associated UAF elements.

Once the SysML problem domain block is defined, the following steps are performed to define the SoI architecture by MagicGrid, which include: (i) creating a solution domain model for the specific SoI (Figure 4, third step), which establishes a precise cross-discipline logical architecture to address the problem defined in the problem domain model; (ii) creating an abstraction relationship between the solution domain model and the problem domain (Figure 4, fourth step) to specify which logical subsystems are derived from what conceptual subsystems in the problem domain model; (iii) defining the solution domain model as a subtype of the UAF resource (Figure 4, fifth step), which enables the redefinition of UAF resources at the SoS level with greater precision through SysML system models; (iv) creating a system configuration model (Figure 4, sixth step) to build the integrated model of the entire SoI; and (v) inheriting all structural and behavioral features of the system configuration model from the solution domain model (Figure 4, seventh step).

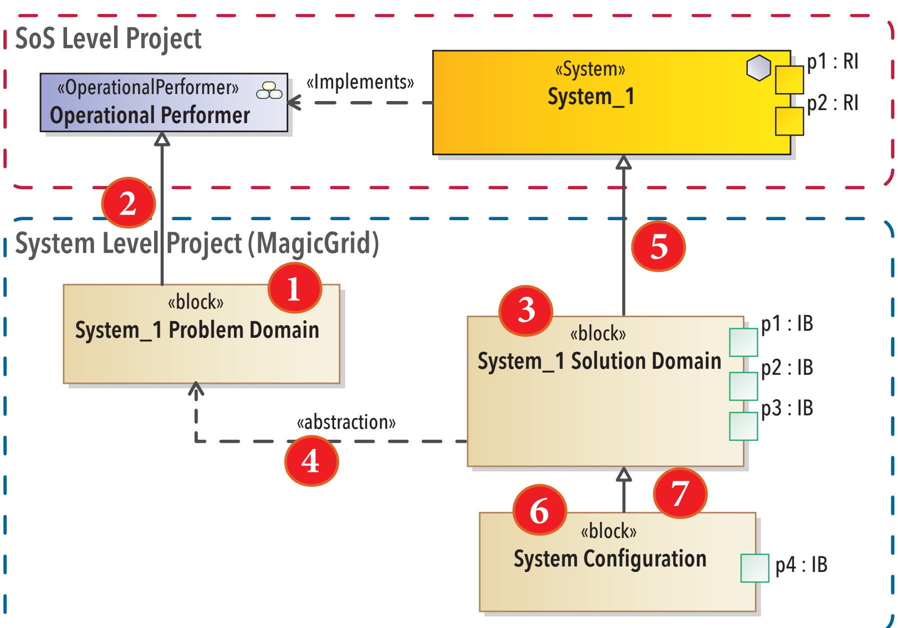


Figure 4. *SysML system models association with UAF resource configuration*

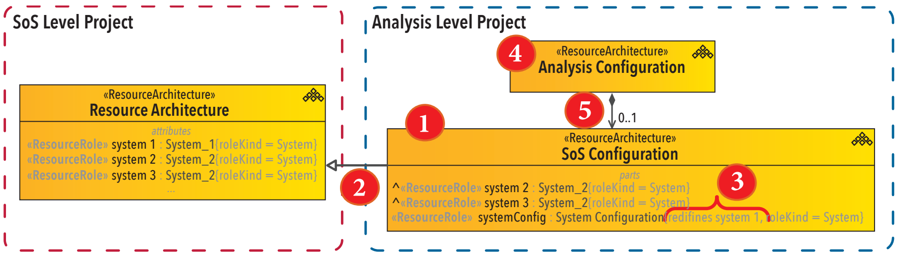


Figure 5. Analysis configuration along with SysML system models in an integrated UAF resource configuration

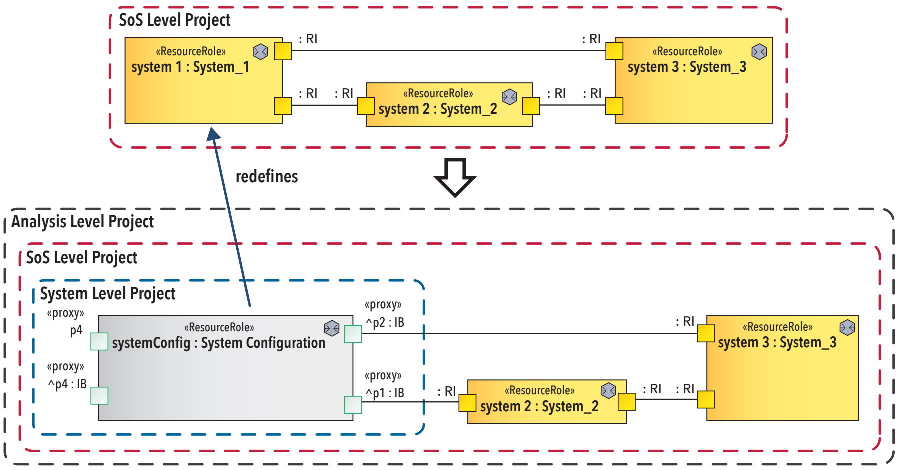


Figure 6. UAF resources internal connectivity model with SysML system configuration

Analysis Level Project

The following level is the analysis level defining the analysis configuration for a specific analysis of the SoS architecture.

As illustrated in Figure 5, the analysis level involves the following steps: (i) creating the *resource architecture* as a SoS configuration, which serves as a placeholder for integrating the SysML system model into UAF resource configuration (Figure 5, first step); (ii) defining the SoS configuration as a subtype of the UAF resource (Figure 5, second step); (iii) redefining the UAF resource by utilizing a more precise SysML system model (Figure 5, third step); (iv) creating the *resource architecture* as an analysis configuration for a specific analysis, which serves as the analysis context (Figure 5, fourth step); and (v) establishing a directed composition relationship from the analysis configuration to the SoS configuration (Figure 5, fifth step). In this manner, the analysis configuration reflects the structure of the SoS being analyzed.

Figure 6 depicts the resources internal connectivity viewpoint from the perspective of the analysis level project. Here, the UAF resource (*system 1*) is redefined with a more precise SysML system model (*system configuration*). Consequently, this architecture enables the co-execution of SysML system models within an integrated UAF resource configuration.

The process describing how to co-execute system models in SysML in the integrated UAF resource configuration is shown below, in Figure 7.

A CASE STUDY ON THE APPLICATION OF THE PROPOSED APPROACH

For this case study, we decided to show how the proposed approach can be applied to an urban transportation SoS, where traditional internal combustion engine (ICE) vehicles could be deemed outdated in terms of cost and sustainability. Currently, there is a real demand for cities to reduce pollution and be sustainable; therefore, modernization of public transportation could be an option to achieve these goals.

As electric bus technology reaches technological maturity and becomes more cost-effective, it could be considered a viable option for a public transportation system. However, an electric bus fleet requires an extensive charger network, capable electric infrastructure, and a precisely organized operation. Thus, our goal in this case study is to analyze this SoS from a cost perspective. Following the proposed approach, we first determine the structure of the SoS using the resource connectivity diagram and define capabilities along with requirements, as shown in Figure 8.

Modern technologies are not yet capable of recharging electric bus batteries as quickly as traditional ICE transport can be refueled. As a result, the electric bus fleet requires constant battery recharging. Therefore, this characteristic of the system needs to be carefully evaluated before proving that the electric bus fleet is feasible both from an economical and operational point of view. This case study will focus on this system's characteristics, but proper SoS studies should cover all the characteristics of the system. Due to the scope associated with urban transportation SoS, it is very difficult to showcase such an analysis in this case study; thus, we will narrow our focus to economical and operational feasibility.

To perform this analysis, it is important to know how the internal systems of SoS interact with each other. The defined internal SoS connectivity is shown in Figure 9. In this diagram, we can see that the electric bus fleet, charging station, and park operator systems are in constant connection. We assume that electric buses use traditional battery technology, making it necessary to connect them to a network of chargers. Since today's electric buses have enough battery capacity to cover public transportation routes for one day, charging should be handled at night. This reduces the stress

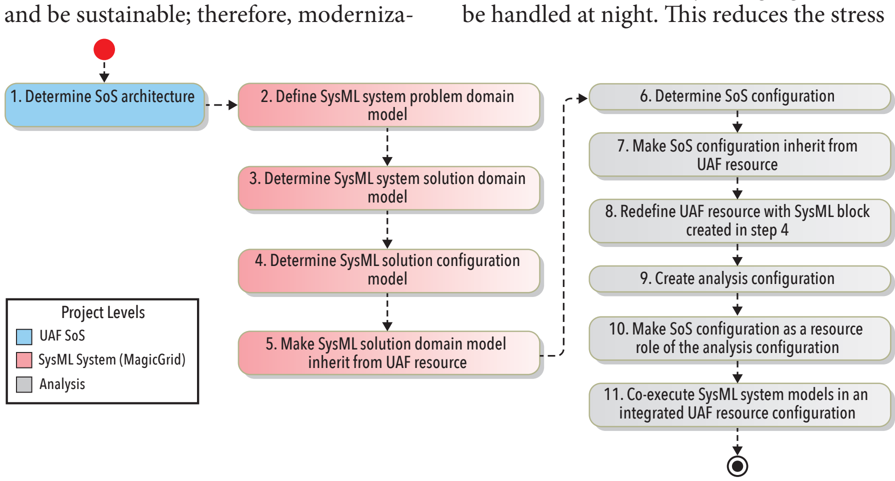


Figure 7. Process of co-executing SysML system models within UAF resource configuration

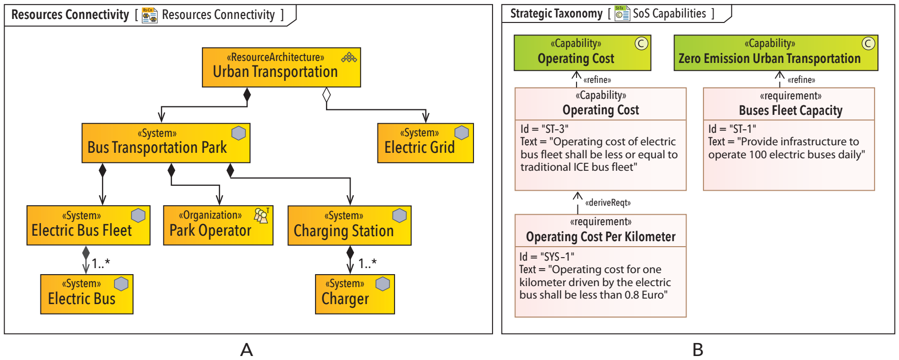
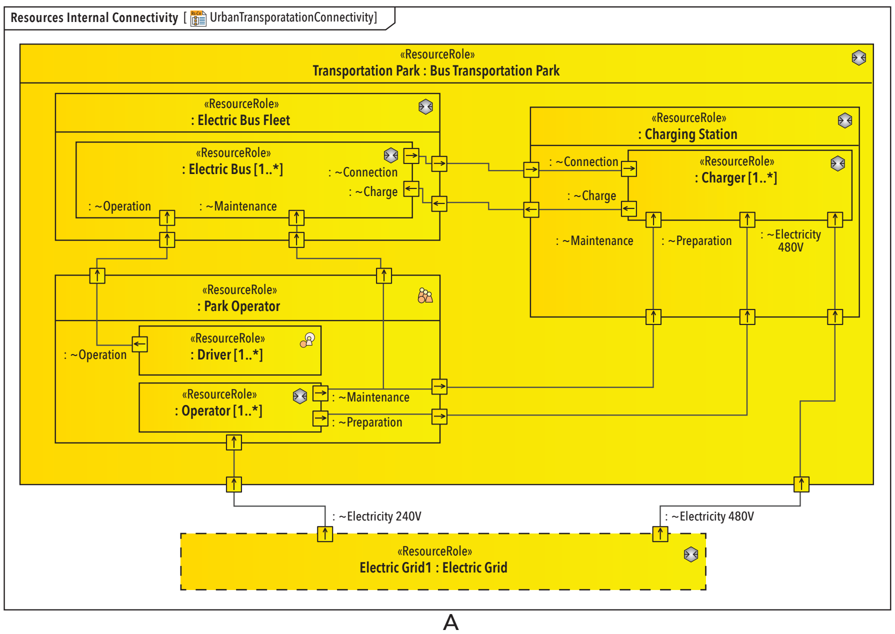


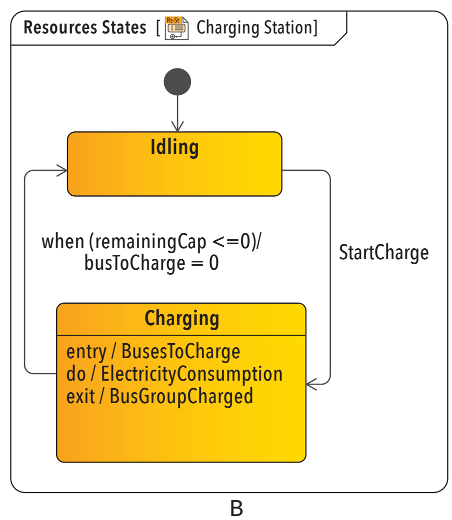
Figure 8. A) Urban transportation SoS structural composition; B) Urban transportation required capabilities and requirements

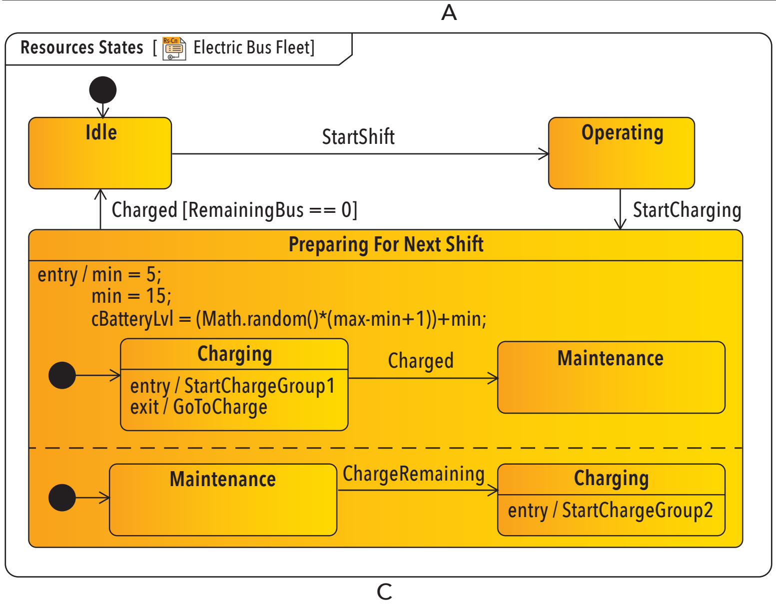
to an electric grid and allows for cheaper electricity prices but requires planning and bus transportation park operation. Thus, the behavior model needs to be introduced in our SoS analysis. Figure 9 shows state diagrams of SoS systems:

As stated before, in this case study we are examining the feasibility from a cost perspective to operate electric buses for a modern urban transportation system. This is evaluated by finding the price of the value per kilometer, which is the MoE of SoS that we will analyze. To find this parameter value, we introduce the parametric model into our SoS model, as shown in Figure 10 Part A. The price per kilometer parameter can be categorized as a stochastic SoS property, since its value depends on other SoS properties that can change randomly during the electric bus fleet operation lifecycle, including the average bus route distance, the electricity price, the remaining battery capacity of the bus, the operating days, etc. For this reason, this case study uses the Monte Carlo simulation method to calculate the price per kilometer MoE value.

Since the Monte Carlo simulation method and required model artifacts can be considered as elements that do not







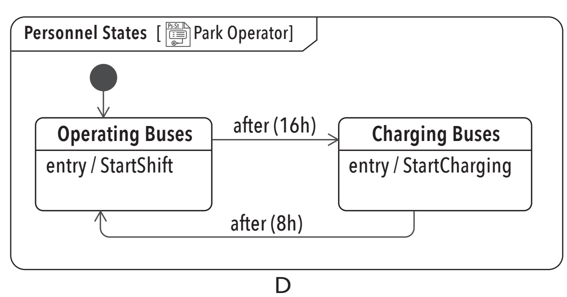


Figure 9. A) Urban transportation internal connectivity; B) Charging depot resource state; C) Electric bus fleet resource state; D) Park operator personal state diagrams

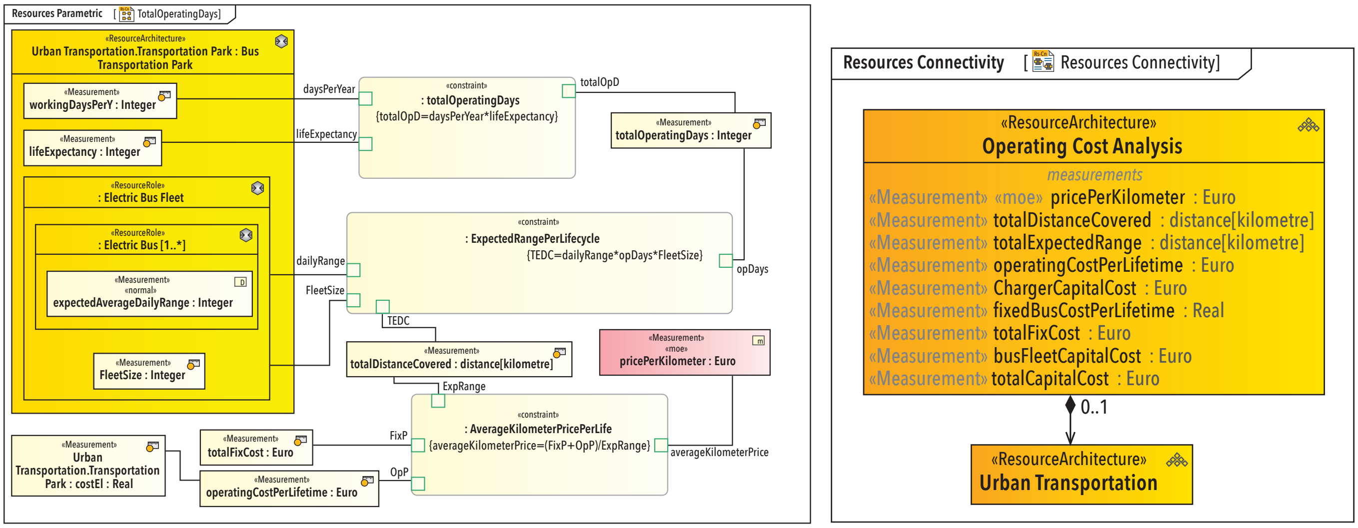


Figure 10. A) Parametric for calculating electric bus one kilometer price; B) Introduction of operating cost analysis element into SoS model

describe the studied SoS architecture, we introduce an additional element that will be responsible for applying the required simulation techniques in the SoS model. Figure 10 Part B shows this application in our case study model.

After defining state machines, parametric and Monte Carlo simulation techniques in our SoS model, the case study is executed to find the operating cost for the electric bus fleet. Since the operating time of one average bus is considered to be around 10 years, the simulation is run during this period. For the Monte Carlo analysis, 10,000 iterations of the simulation were executed, and the results are presented in Table 1 and Figure 11.

According to the results of the analysis of the operating cost of the electric bus fleet per kilometer, the cost meets the associated requirement (Figure 8) but is only slightly below the required value. This poses a potential risk to the effective operation of the urban transportation SoS, given its reliance on several contingent parameters. It is important to note that while the mean value of the operating cost is close to the specified requirement value, real-world urban transportation deployments may result in higher operating costs. Therefore, it is advisable to aim for an operating cost value that is at least one standard deviation below the mean value rather than the mean value of the analysis. However, we will not delve into this analysis in our case study example and suggest that the analyzed SoS should seek additional enhancements.

Table 1. Operating Cost per Kilometer mean and standard deviation values

	Mean Value, Euro	Standard Deviation, Euro	Runs, No.
Operating Cost per Kilometer, Euro	0.7940	0.0643	10 000

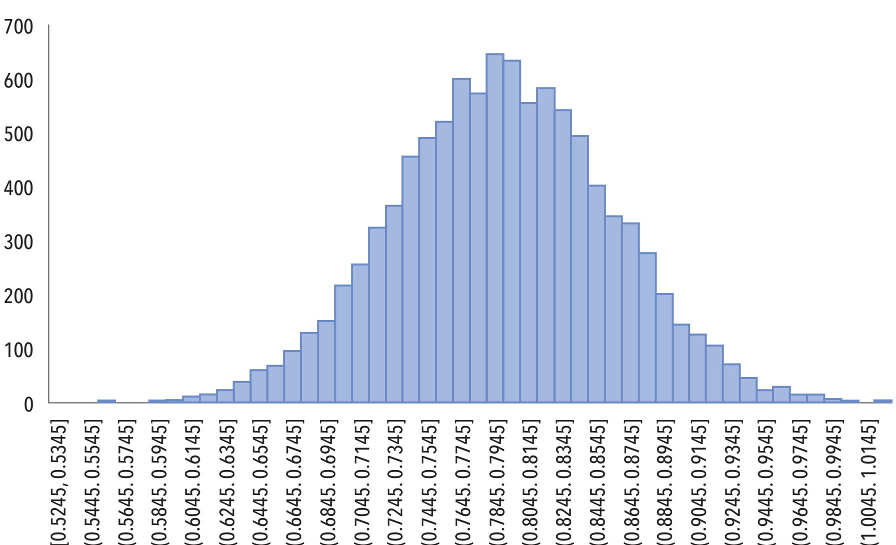


Figure 11. Histogram of operating cost per kilometer parameter for urban transportation SoS

The proposed approach assumes that SysML models are used to analyze each system that comprises a System of Systems (SoS) at the system level. In this case study, we focus on the bus transportation system that is provided for further analysis to improve the operating cost of the entire SoS. As a result, the engineering team in charge of the electric bus fleet system offers a new system solution that includes the electric generation system (EGS). Figure 12 shows the configuration of SoS and system models according to the proposed approach.

Analysis of bus transportation leads to new developments in this system. This new evolution of the system needs to be fed back into the urban transportation SoS architecture model. Utilizing the proposed approach, a new SoS configuration element is created that inherits the existing urban transportation architecture (Figure 8 Part A) and redefines the bus transportation part with a bus fleet configuration block that is supplied from the system level model. This configuration of the model is shown in Figure 13. In addition, the operating cost analysis element is retained as before in the case study. This element permits us to configure the urban transportation SoS

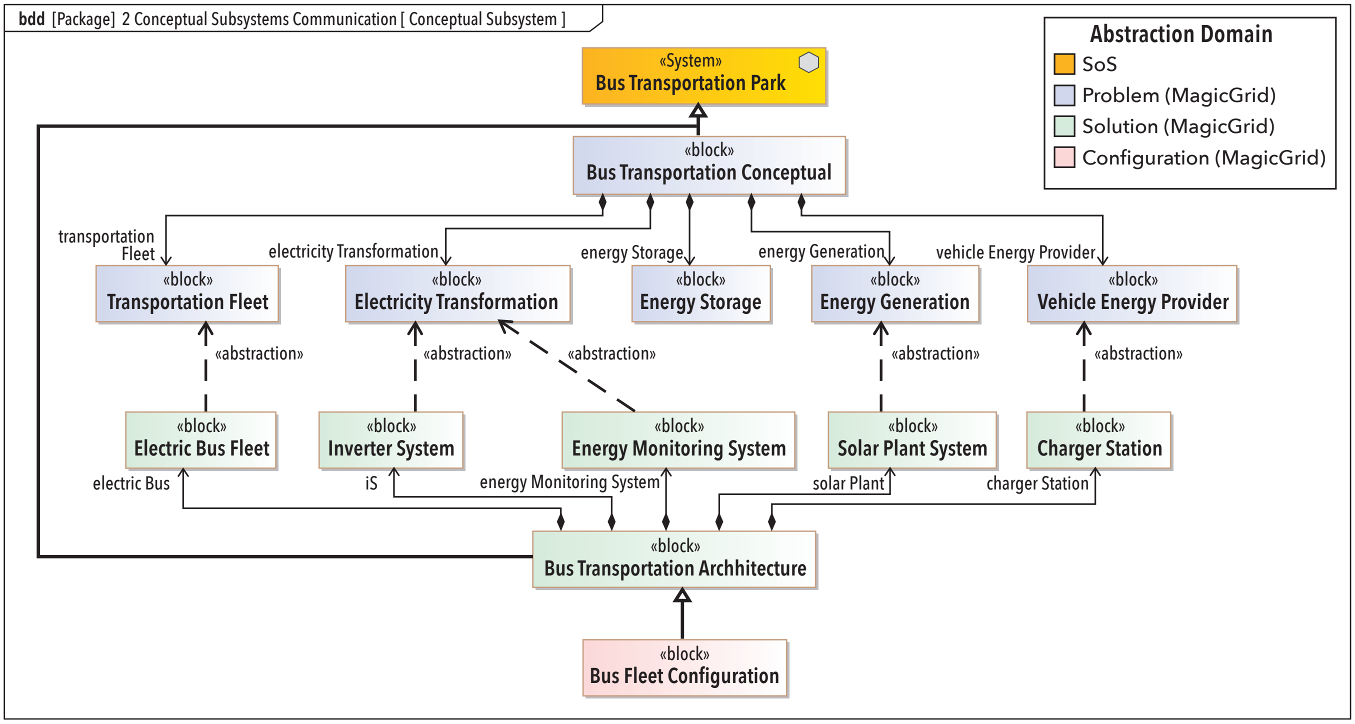


Figure 12. SoS bus transportation park transition to system level that is completed with MagicGrid

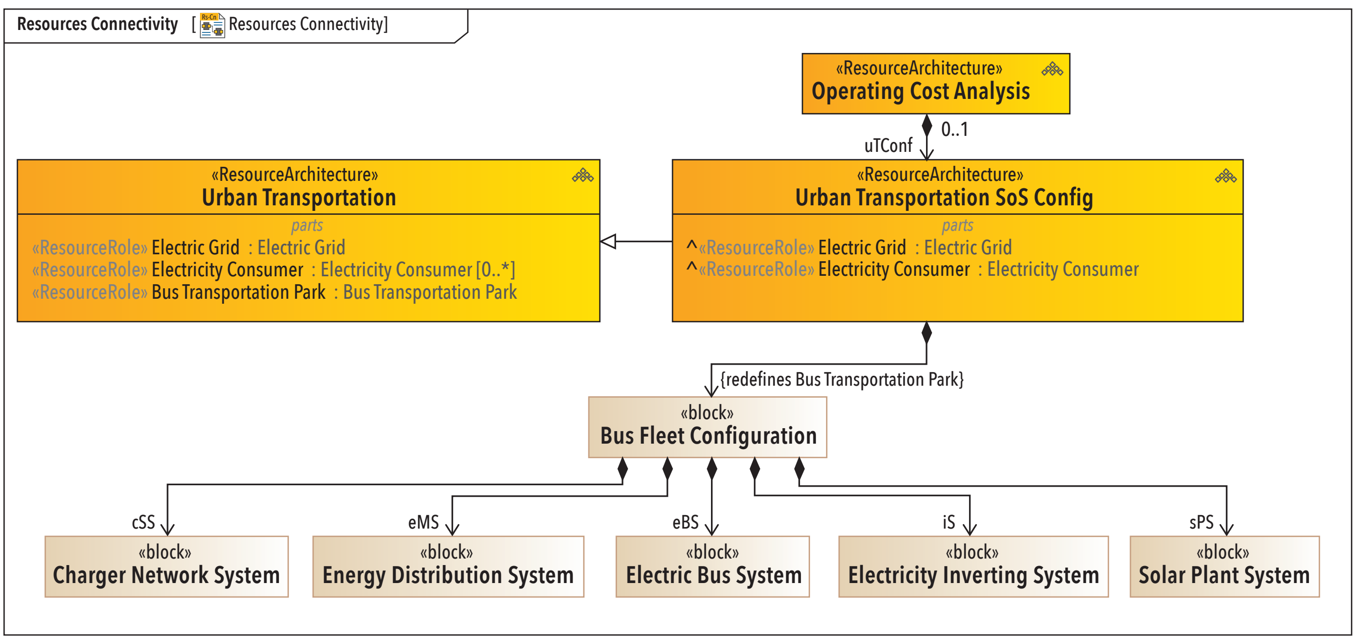


Figure 13. Urban transportation configuration with redefined bus fleet system

simulation to calculate the operating cost per kilometer value, taking into account the updated architecture of the SoS.

After the update, the cost calculation is performed with the new SoS architecture variant. The same simulation methods are used as before: for the stochastic aspect of SoS, the Monte Carlo simulation is used, while individual SoS systems behaviors are defined with state and activity diagrams and a parametric model is used to calculate the parameter value (Figure 9 and Figure 10 Part A). The results of the Monte Carlo after updating the architecture of urban transportation SoS are presented in Table 2.

The simulation, as before, was executed 10,000 times. The histogram of the simulation results is shown in Figure 14.

The new simulation results show that introducing a solar power plant reduces the operating cost for one driven kilometer for an electric bus. However, it should be noted that the standard deviation value is higher than the previous simulation results. This could be associated with an increase in capital costs required for solar plant investment, which introduces the dependence of SoS on cheap electricity prices and higher volatility of operating costs. Furthermore, it should be emphasized, that despite the operating cost mean value being in close proximity to the specified requirement value, it is probable that actual urban transportation deployments will incur higher operating costs. As such, the operating cost value should not target the

Table 2. Operating Cost per Kilometer mean and standard deviation values after updating Urban Transportation SoS

	Mean Value, Euro	Standard Deviation, Euro	Runs, No.
Operating Cost per Kilometer, Euro	0.7509	0.0831	10 000

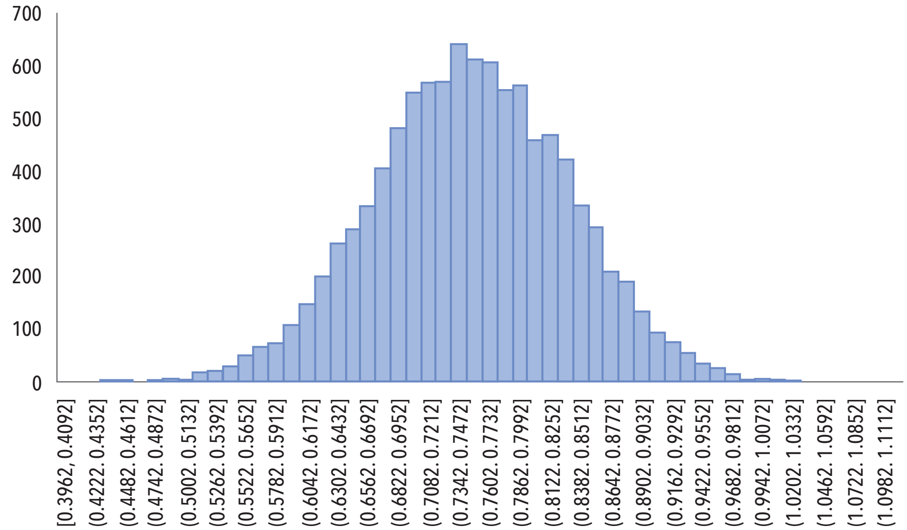


Figure 14. Histogram of operating cost per kilometer parameter for urban transportation SoS after architecture update

mean value of the histogram, but rather a value that is at least one standard deviation below the mean value. Nonetheless, in the present case study example, we will not conduct that analysis and instead advise that the analyzed SoS should focus on seeking further enhancements.

Finally, in the case study, only one of the SoS systems was redefined, but the proposed approach allows redefining any required systems of the SoS. In addition, it is worth noting that from this case study it was understood that the most sensible approach is to redefine the atomic systems of SoS, since this allows straightforward system model integration into a SoS model.

CONCLUSIONS

The analysis of related works revealed that even if there are some studies addressing transitions between SoS and system models, they are very high-level guidelines as opposed to detailed step by step instructions. Details are especially important when we deal with the precision required to co-execute models. These details are dictated by the frameworks, metamodels, and languages that are used to model systems and SoS.

For this study we use MagicGrid as a framework and SysML as the standard language to model systems, and UAF as the framework and UAFML as the language to model enterprise architectures. We propose an approach for end-to-end co-execution of the integrated enterprise model. In the proposed approach, we assume that each system the SoS consists of at the system level is modeled either with SysML or other modeling techniques. If other modeling techniques are used, models need to be imported into the UAF environment as functional mock-up units (FMU). UAF resources that are not detailed in SysML or other modeling technique must be excluded from co-simulation configuration.

Our proposed approach is verified by the urban transportation SoS case study. We explore the feasibility from a cost perspective to operate electric buses in a modern urban transportation system. The case study revealed that the proposed approach allows us to apply engineering analysis techniques like SysML parametrics, behavioral simulation, and Monte Carlo simulation. It also revealed that it is best to detail the lowest level system models in the SoS scenario; the higher-level system modifications should be kept inside the SoS model.

This case study demonstrates how the proposed approach can be used to verify SysML requirements. The approach uses simplified requirements verification technique described in Morkevicius and Jankevicius (2015). We look forward to applying the proposed approach to different real-world problems, to test its applicability with different types of analysis techniques, such as trade studies, what-if analysis, and other types of requirements verification. ■

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A Geo-Spatial Method for Calculating BEV Charging Inconvenience using Publicly Available Data

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ABSTRACT
As governments and the automotive industry push towards electrification, it becomes increasingly critical to address the factors which influence individual car buying decisions. Evidence suggests that operational inconvenience or the perception thereof plays a large role in consumer decisions concerning battery electric vehicles (BEVs). BEV ownership inconvenience and its causal factors have been relatively understudied, rendering efforts to mitigate the issues insufficiently informed. This paper presents a method of producing an empirical equation which relates operational inconvenience to a small number of housing and local electric vehicle supply equipment (EVSE) infrastructure factors. The paper then further provides a method of applying the equation in a geo-spatial context allowing for the evaluation of the effects of policies in a geographical manner. this method enables future quantitative analyses concerning investment in EVSE infrastructure to be directly sensitive to BEV operational inconvenience due to charging.

INTRODUCTION

The wide-spread adoption of BEVs for personal use is imperative in the realization of a green transportation future in the US. To achieve high rates of adoption in the near and medium term future, policy makers and industry have recently set ambitious goals for BEV market penetration (Person and Mason 2021). The degree to which BEV adoption will mitigate the environmental impact of the transportation sector is the subject of extensive and accelerating academic debate (Dolganova et al. 2020) and is contingent on related developments in the power generation sector. The trend in the power generation sector is towards decreased carbon intensity (US Environmental Protection Agency 2023b) implying that even current production BEVs will see reduced per-mile emissions within their terms-of-use. Ultimately, the success of BEV adoption initiatives will be the result of many millions of decisions made by individual consumers with different priorities. While much attention has been paid to the economic aspects of the decision to purchase BEV evidence suggests that consumers also strongly weight perceived operational convenience in their decision making process (Kwon, Son, and Jang 2020; Neaimeh et al. 2017; Vassileva and Campillo 2017).

It is entirely rational to assume that operating a BEV will be more inconvenient than operating an internal combustion vehicle (ICV) due to the time required to charge. BEV charging adds range at a much lower rate than ICV fueling even at the highest charging rates currently available (US Department of Transportation 2022). Thus, BEVs should spend more time charging than ICVs spend fueling for an equivalent distance

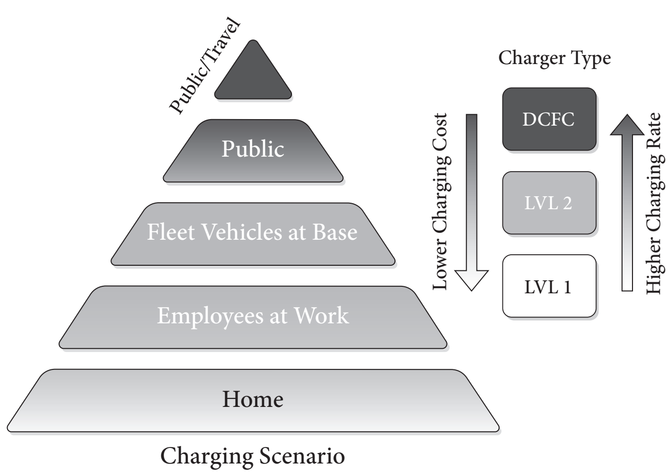


Figure 1. Charging activity pyramid. Modified composite of original graphic by T. Bohn, Argonne National Laboratory (from Rabinowitz et al. 2023b)

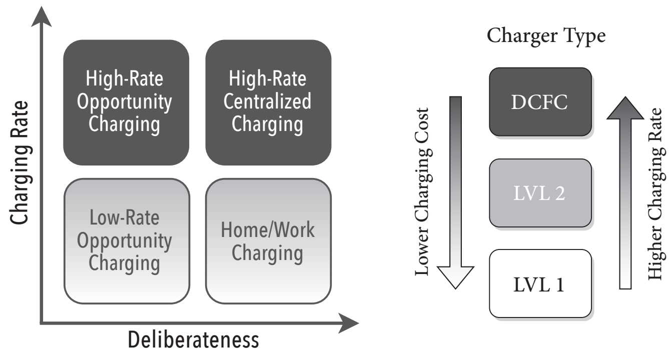


Figure 2. Dual-axis charging activity model; high-rate opportunity charging is rarely available.

driven. This reality will affect BEV operators unevenly. Those with higher energy usage will need to charge their vehicles for longer and/or more often. Inequity will also result from different levels of access to EVSE.

A common model for BEV charging is the "charging pyramid" model as shown in Figure 1. In essence, the charging pyramid model states that the frequency of charge events will be inversely proportional to the rate at which the events occur. Explicitly, the charging pyramid model views home and work charging as fundamental as evidenced by their presence at the base of the pyramid.

As recently as 2021 electric vehicle (EV) sales constituted less than 4% of new car sales (EV Adoption 2022). With such a low volume of sales it would be safe to assume that the majority of BEV buyers are in relatively favorable BEV ownership situations. In order for BEVs to achieve a dominant market share in the US, they must be an attractive proposition for most of the market. Residents of owner-occupied single-unit dwellings make up about 62% of Americans per the 2021 American community survey (ACS) (US Census Bureau 2021) while residents of owner-occupied dwellings of all types make up roughly 68%. People who either do not own their residences or live in high density housing may not be able to install EV chargers for a variety of reasons. There are also a large number of Americans for whom work charging is not an option. As of 2021, just fewer than 10,000 workplace EVSE ports existed in the entire US (Brown, Schayowitz, and Klotz 2021). Thus, an important fraction of the population will not have access to home or work charging. It is worth considering what charging options are available to the portion of the market unable to charge at home or at work. The authors propose that charge events can be categorized by rate and deliberateness as in Figure 2.

As can be seen in Figure 2, the proposed model characterizes charging events by rate and deliberateness. In this case, deliberateness is the degree to which the charging event requires the operator to plan around it. To charge at home, work, or a centralized charging station, the operator must travel to a specific destination. This is opposed to opportunity charging wherein the operator travels to a given location (gym, retail, entertainment) for another purpose and charges at an available charger near the location.

Opportunity charging is most commonly low rate while high-rate charging is most commonly available in centralized locations such as dedicated stations on interstate highways (Trinko et al. 2021). High-rate opportunity charging is rarely available and thus not usually an option for EV operators. Thus, those who cannot charge at home or work are reliant on public infrastructure which is often limited to high-rate centralized charging and low-rate opportunity charging. The experiences of this demographic will depend heavily on the characteristics of local EVSE infrastructure. To evaluate the effectiveness of EVSE infrastructure investment in terms of its effect on those who rely upon it a new under-standing must be attained. In this paper a novel, quantitative, and geographical method for evaluating the inconvenience of BEV ownership for all demographics of potential BEV operators is presented. This metric and method provide the foundation for future inconvenience-sensitive EVSE infrastructure analysis.

ENERGIZING INCONVENIENCE

In a previous paper (Rabinowitz et al. 2023a), the authors proposed a metric (SIC) which reflects this understanding of inconvenience. A BEV operator is only inconvenienced by charging their vehicle if they must devote time to doing so in which they are unable to, or have a limited ability to, perform other activities. For example, if a BEV owner parks at home and immediately begins charging his or her car then the amount of time dedicated to charging is only the time required to plug the car in and to un-plug it later. The inconvenience is minimal regardless of the duration of the charging event. Conversely, if one charges at a public charging station then he or she must remain at that location for the duration of the charge and is inconvenienced for the entire duration of the charge as well as the time required to travel to and back from the station. Relative to inconvenience, charging events may be broken down into four categories as follows:

- Home charging events: Charging events which take place at the operator's home location. The operator's vehicle will normally dwell at home for long periods on a daily basis. Thus, home charging events, regardless of duration, do not force the operator to devote time out of his or her itinerary to charging.
- Work charging events: Charging events which take place at the operator's work location. The operator's vehicle will normally dwell at work for long periods on workdays. Thus, work charging events, regardless of duration, do not force the operator to devote time out of his or her itinerary to charging.
- Destination charging events: Charging events which take place at long dwell destinations such as supermarkets, retail centers, gyms, etc. Because the operator would visit these locations regardless of whether he or she intended to energize a vehicle, these events do not force the operator to devote time out of his or her itinerary to charging. Thus, destination charging events only inconvenience the operator for time that he or she would need to spend paying for the charging event.
- En-route charging events: Charging events which take place at a location which the operator visits specifically to energize a vehicle. Locations such as petroleum stations or centralized direct current (DC) fast charging (DCFC) charging stations may be located near amenities but operators will generally be constrained to stay within a small area adjacent to the station for the duration of the charging event. Thus, operators are inconvenienced for the duration of the event and payment process. An assumption is also made that operators will have to travel a non-negligible distance to the charging station. Because operators are only traveling to the station to energize their vehicles the travel time is also considered to be devoted charging time. Thus, operators are also inconvenienced for the travel time required to get to and from the charging station.

Because the different types of charging events effect the operator differently it is important to define a metric of inconvenience which can account for all four. To this end the authors propose a flexible metric, inconvenience score (SIC) defined as

$$S_{IC} = \frac{\sum_{k=1}^{N}\left[D_{E,k}M_{E,k} + D_{T,k}M_{T,k} + D_{P,k}M_{P,k}\right]}{\sum_{k=0}^{N}L_k} \qquad (1)$$

for an itinerary of N trips where D_E is the duration of the charging event, D_T is the duration of travel to get to the charging location, DP is the duration of the payment process, $M_{E,\,k}$, $M_{T,\,k}$, and $M_{P,k}$ are integer multipliers which respectively define whether or not to count the various durations for trip k, and L_k is the length of trip k in kilometers. S_{IC}, thus, is the average dedicated charging time per kilometer traveled in a given itinerary. The values of the multipliers based on the type of charging event are shown in Table 1.

Table 1. Values of multipliers based on charging event type

Energizing Event Type	M_E	M_T	M_P
Home	0	0	0
Work	0	0	0
Destination	0	0	1
En-route	1	1	1

So defined, S_{IC} is able to account for the differences between charging event types and to account for differences in total travel distance between itineraries. The flexibility of the S_{IC} metric thus allows for the direct comparison of inconvenience between disparate itineraries.

ITINERARY DATA

Itinerary data for this study was based on the 2017 National Highway Transportation Survey (NHTS) (US Department of Transportation 2017). The decision to use NHTS data was taken due to the scope and information content of the survey when compared to other publicly available datasets.

The NHTS is a comprehensive non-commercial travel survey conducted by the US FHA which serves as an authoritative source on travel behavior in the US. The most recent NHTS was conducted in 2017. The NHTS collects, by survey, travel activities for selected households for a single day. The surveyed households are located in all 50 US states and the District of Columbia. Data collected includes demographic data for the household as well as travel itineraries for each person and vehicle within the household. The publicly available version of the 2017 NHTS contains single day itinerary data for 117,222 households containing 219,194 persons and 153,351 vehicles. Because the daily itinerary distances for vehicles in the 2017 NHTS are more varied than trip counts, the decision was made to scale by distance in this paper.

The format of the NHTS is not ideal for use in longitudinal analysis due to the single day itineraries. Using NHTS data for longitudinal analysis requires one to derive long term itineraries from single day itineraries. Additionally, because NHTS offers neither precise home locations nor precise destination locations, it is not possible to construct household activity pattern problems (HAPPs) (Recker 1995) as was done in (Kang and Recker 2014) using California household travel survey (CHTS) data. However, NHTS data does enable more demographic selection than any other comparable study and thus enables the most specific results to be attained. To use NHTS data for long term itineraries, the single day itineraries were simply tiled for a given number of repetitions.

Calculating Inconvenience Score

For any given itinerary, operators will experience different levels of inconvenience based on how they choose to schedule charging events. The authors contend that the fundamental inconvenience for a given itinerary is the minimum inconvenience for said itinerary. To calculate the minimum inconvenience for a given itinerary optimal charge scheduling was used.

Optimal charge scheduling was conducted via dynamic programming (DP) (Bellman 1956; Kirk 1970). DP is a commonly used technique in optimal control which is guaranteed to find a globally optimal solution subject to the chosen discretization of the problem.

The goal of the optimization was

$$\min_{\overline{U}} J(S_0,\overline{U}) \tag{2}$$

where

$$J(S_0,\overline{U}) = \Phi(S_N) + \sum_{k=1}^{N} \Psi(S_k, U_k) \tag{3}$$

$$S_{k+1} = f(S_k, U_k), \quad k=0,\ldots,N\text{-}1 \tag{4}$$

$$S_{min} \le S(t) \le S_{max} \tag{5}$$

where $\Psi(\overline{S},\overline{U})$ is the running cost (charging inconvenience), $\Phi(\overline{S})$ is the final state cost, $\overline{S} = [SOC]$ is the state vector containing the battery state of charge (SOC) for the vehicle, $\overline{U}$ is the control vector formulated as $\overline{U} = [D_D, D_{ER}]^\top$ containing durations of opportunity charging events at destinations C_D and durations of en-route charging events at centralized high-rate charging stations C_{ER}, J is the cost for S and U, and S_{min} and S_{max} are lower and upper limits for the state vector and are constant in time. The overline indicates an array containing values at multiple discrete time intervals. The goal of the optimization is to find the optimal charging schedule ($\overline{U}$*) such that J* is equal to the global minimum value for J. J is the inconvenience score (S_{IC}) as defined in equation (1) which accounts for total dedicated charging time.

VEHICLE MODEL

For evaluation purposes, a vehicle model was defined which simulates the amount of energy consumed by the vehicle on a given trip based on the trip length and mean speed. The vehicle model is defined by the parameters listed in Table 2.

Table 2. Vehicle parameters

Parameter	Description
Energy Storage Capacity [kWh]	Maximum amount of energy that can be stored on vehicle [J]
City Consumption Rate [kJ/km]	Amount of energy consumed per unit distance [J/m] in urban driving conditions [less than 15.6 m/s]
Mixed Consumption Rate [kJ/km]	Amount of energy consumed per unit distance [J/m] in mixed urban and highway driving conditions [15.6 m/s – 29 m/s]
Highway Consumption Rate [kJ/km]	Amount of energy consumed per unit distance [J/m] in highway driving conditions [greater than 29 m/s]

For this study the 2021 Tesla 3 LR was chosen as the baseline vehicle. The consumption data for the 2021 Tesla 3 LR is listed in Table 3.

This is, necessarily, an approximate measure. Data for vehicle energy consumption rates was attained from (Cars.com 2022; EV-Database 2021) and verified with data from (US Environ-

Table 3. Base vehicle energy consumption rates

Parameter	Value
Energy Storage Capacity [kWh]	82
City Consumption Rate [kJ/km]	385.2
Mixed Consumption Rate [kJ/km]	478.8
Highway Consumption Rate [kJ/km]	586.8

mental Protection Agency 2023a) with the city consumption rate calculated from US06 drive cycles, the highway consumption rate calculated from HWFET drive cycles, and the highway consumption rate calculated from FTP drive cycles.

EVSE INFRASTRUCTURE MODEL

It was also necessary to define models for EVSE infrastructure. BEV charging rates were based on the Society of Automotive Engineers (SAE) J1772 standard (Society of Automotive Engineers n.d.) and information from (EV-Database 2021). The following assumptions were made about charging infrastructure:

1. If a home charger is available, then it will be an AC Level 2 charger
2. If a destination charger is available, it will be an AC Level 2 charger
3. All DC Level 2 (LVL 2) charging will be done at 12.1 kW which is the middle of the AC Level 2 range
4. All en-route charging will be done at dedicated DCFC stations with DC Level 1 or 2 chargers
5. At all times, all vehicles are within a certain travel time to the nearest DCFC station regardless of their location.

The infrastructure model assigns chargers to destinations based on the stated assumptions. The assignment of AC Level 2 chargers to home locations is based on a Boolean which determines if there will be chargers at home locations or not. The assignment of chargers to destinations is done by assigning chargers, randomly, to a certain percentage of the locations visited by the vehicles. Because this randomness can have an effect on inconvenience score for a configuration, all configurations are run multiple times and the inconvenience scores for the runs are averaged.

DC charging was modeled on the CC-CV curve model for lithium-ion batteries (Marra et al. 2012). The energy added, as a function of time is

$$dSOE = \frac{P_{DC}}{C_B} \mathrm{t_{cc}} + (1 - \mathrm{e}^{(\lambda_C t_{cv})}) \tag{6}$$

$$P_{DC} = P_{AC}\eta \tag{7}$$

$$\lambda = \frac{P_{DC}}{0.2C_B} \tag{8}$$

where $dSOE$ is the change in state of energy (SOE) over the course of the charge event, P_{AC} is the nominal alternating current (AC) power level of the charge event, η is the efficiency of the conversion between AC and DC, P_{DC} is the DC power of the charge event, t_{cc} is the time spent in the constant current portion of the charge event, tcv is the time spend in the constant voltage portion of the charge event, and C_B is the vehicle's battery capacity. This model defines a relationship wherein charging is linear below 80% SOE and inverse-exponential after as it approaches 100% SOE. For AC charging the model used was a pure linear charging model which cuts off at 100% SOE. These charging traces are illustrated in Figure 3.

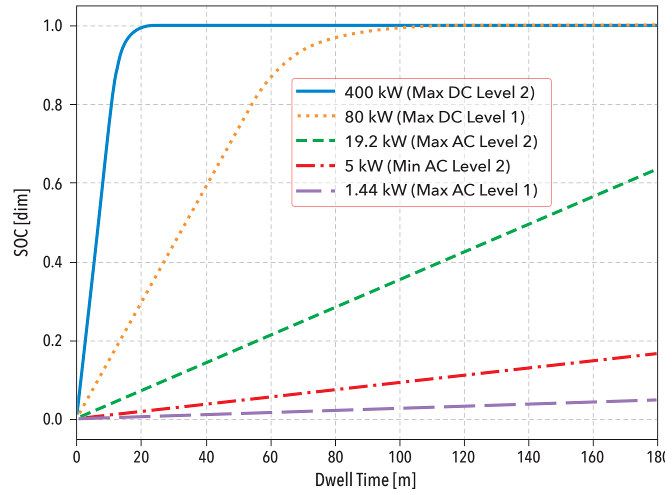


Figure 3. Three hour charging traces at various charging rates for a vehicle with an 80 kWh battery

As seen in Figure 3, charging rate has a significant effect on the amount of time required to charge. At 250 kW, a vehicle with an 80-kWh battery can charge to 80% SOC in about 15 minutes where the same vehicle would require 384 minutes to complete the same charge at 10 kW.

INDIVIDUAL TRACE RESULTS

Because the assignment of destination chargers is probabilistic, the results for a given BEV and set of infrastructure parameters may be different from run to run. Figure 4 demonstrates this by showing three simulation runs of 7 tiled day long itineraries where all vehicle and infrastructure parameters are the same between the simulations.

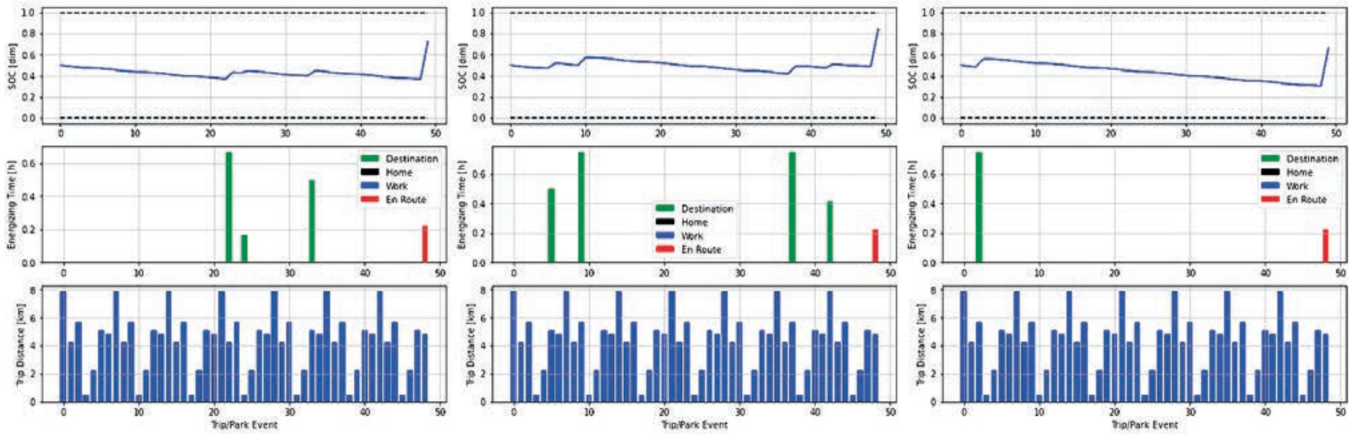
In Figure 4 the vehicle, in all cases, was neither able to charge at home nor at work. The effects of being able to charge at home or work are often visually striking. Because home dwells are long and the operator does not suffer a payment or travel penalty associated with home or work charging events, these events tend to dominate. An example of the effects of home and work charging over a 7 day trace is shown in Figure 5.

Vehicle #48, as shown in Figure 5, had a typical commuter itinerary which was dominated by two long daily trips. For this type of itinerary charging at home and work is particularly important as the vehicle uses a significant amount of its range over a given day. Having the ability to charge at work allows for a much smaller reliance on public charging but the operator will still have to occasionally charge at a destination or centralized charging station. Charging at home has a higher impact as it removes the need to charge anywhere else for normal daily driving as seen in panel (c).

INCONVENIENCE FORMULAE

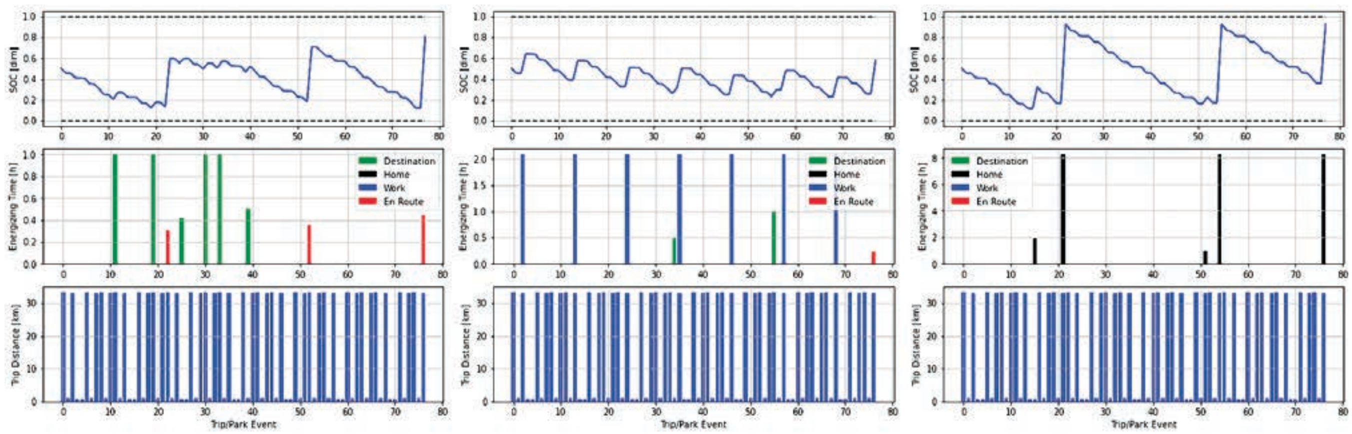
Having derived a model for energizing inconvenience an experiment was run concerning several vehicle and EVSE infrastructure parameters. The purpose of this experiment was to derive an empirical formula for inconvenience score based on vehicular and infrastructural parameters. The experiment was a full factorial design on the parameters listed in Table 4.

The rationale for these levels was to capture the realistic range of values for each parameter in the present and near future. The range of battery capacities was based on the values of usable battery capacity found in (EV-Database 2023). The range for DCFCR was based on ranges identified in (EV Database 2021; Trinko et al. 2021). It would be quite difficult to find a true range of values for DCL or DCFCP, but these values were estimated by comparing the



(a) Simulation #1 of Vehicle #105 (b) Simulation #2 of Vehicle #105 (c) Simulation #3 of Vehicle #105

Figure 4. Traces for BEVs with no home or work charging and identical vehicle and infrastructure parameters



(a) Vehicle #48 without home or work charging (b) Vehicle #48 with work charging (c) Vehicle #48 with home and work charging

Figure 5. Traces for BEVs with no home or work charging and identical vehicle and infrastructure parameters

Table 4. Experiment parameters and levels

Parameter	Levels	Unit
Home Charging (HC)	[False, True]	Boolean
Work Charging (WC)	[False, True]	Boolean
Battery Capacity (BC)	[40, 80, 120]	kWh
Destination Charger Likelihood (DCL)	[0, 4.5, 15]	%
DCFC Rate (DCFCR)	[50, 150, 250]	kW
DCFC Penalty (DCFCP)	[0, 25, 50]	min

numbers of different types of chargers present at different types of locations identified in Trinko et al. (2021) with statistics about numbers and geographical distributions of petroleum fueling stations found in American Petroleum Institute (2023). The ranges of values used for DCL and DCFCP were also in line with calculated values for the Denver, Colorado urbanized area as discussed later.

The electric vehicle model used for energy consumption was the Tesla 3 LR model described in Tables 2 and 3 with BC being the only parameter modified during the experiment. For each of the 324 experimental cases, inconvenience scores were generated for all 61,039 itineraries from vehicles in the 2017 NHTS containing

Table 5. Model summary

R	R-Squared	Adjusted R-Squared	Std. Error
0.991	0.982	0.978	0.000

Table 6. ANOVA

Category	Sum of Squares	DOF	Mean Squares
Model	10.100	63	0.160
Error	0.181	260	0.001
total	10.281	323	0.032
F Statistic		*P*(> *F*)	
290.509		3.504 exp(−200)	

more than 3 trips. A linear regression was then performed on all min-max normalized terms and interactions. Significant results for this regression ($\alpha = 0.05$) are presented in Tables 5, 6, and 7.

The significant coefficients from the regression are also shown visually in Figure 6.

The regression was performed with normalized regressor values to remove the impact of the scales of the regressors. Thus normalized, it is possible to make a comparative analysis of the importance of the parameters and their interactions. Of the parameters BC, HC, DCL and DCFCR were shown to contribute to decreasing inconvenience while DCFCP was shown to contribute to decreasing inconvenience. Of the parameters, the most important for reducing inconvenience was HC. As discussed previously, BEV operators who can charge at home rarely need to charge anywhere else to complete their daily driving. The dominance of home charging is further borne out in the primary interaction terms where all interactions with HC strongly counteract the impacts of the primary terms. It is also worth noting that, while the rate of high rate charging matters in reducing inconvenience, the penalty for having to travel to a fast charging center is quite large and thus, for many BEV operators, traveling to a fast charging station will not be an attractive option.

Table 7. Significant coefficients

Coefficient	Value	*F* Statistic	*P*(> *F*)
Intercept	0.317	17.297	0.000
HC	-0.291	-11.234	0.000
WC	-0.119	-4.578	0.000
DCL	-0.136	-4.784	0.000
HC:WC	0.117	3.183	0.002
DCFCR	-0.222	-7.805	0.000
DCFCP	0.629	22.126	0.000
HC:DCL	0.134	3.327	0.001
HC:DCFCR	0.206	5.139	0.000
WC:DCFCR	0.089	2.208	0.028
BC:DCFCP	-0.261	-5.934	0.000
HC:DCFCP	-0.566	-14.074	0.000
WC:DCFCP	-0.235	-5.859	0.000
DCL:DCFCR	0.107	2.441	0.015
DCL:DCFCP	-0.297	-6.751	0.000
HC:BC:DCFCP	0.208	3.349	0.001
HC:WC:DCFCP	0.221	3.893	0.000
HC:DCL:DCFCP	0.293	4.712	0.000

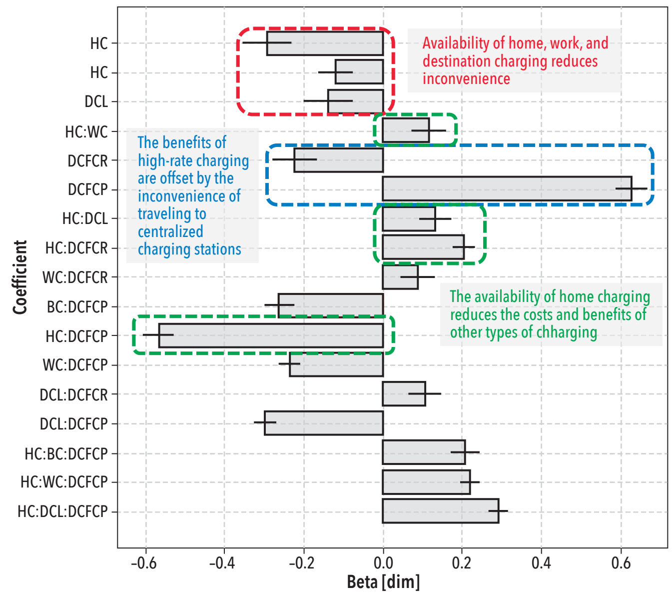


Figure 6. Significant regression coefficients and error bars

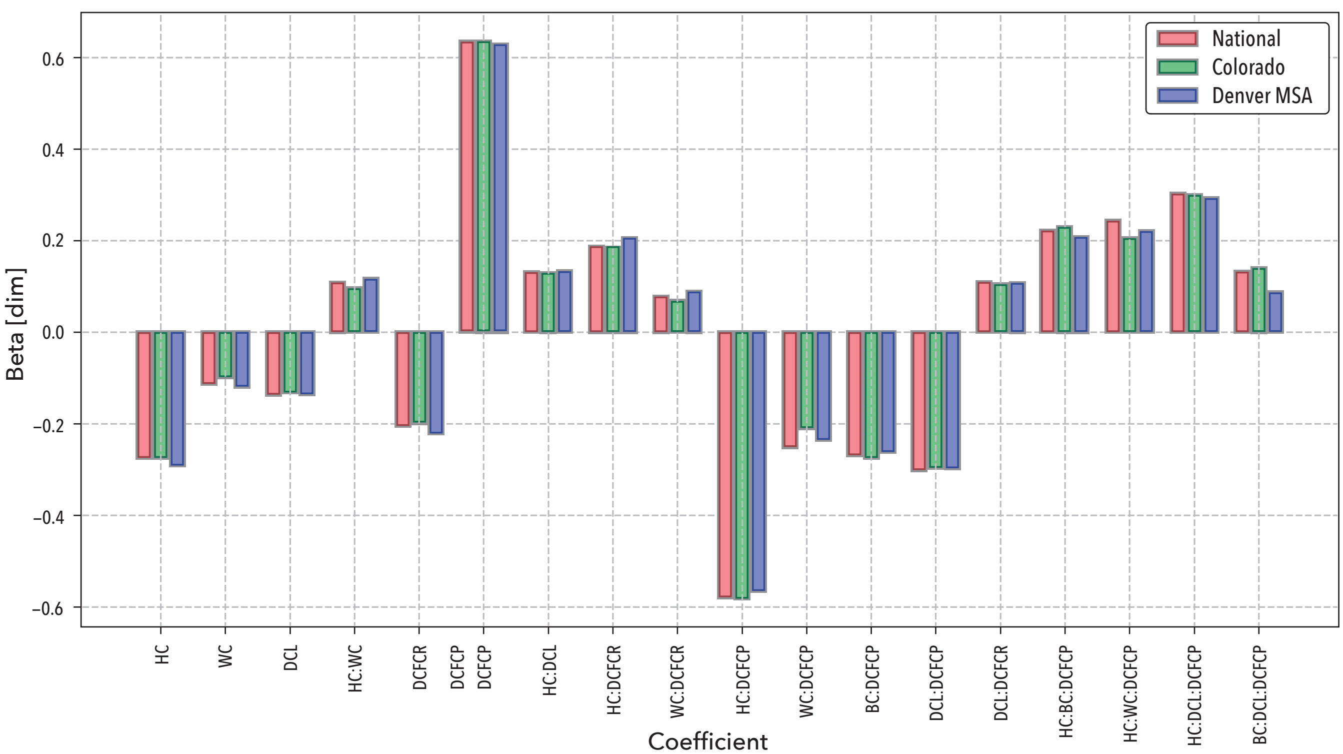


Figure 7. Significant regression coefficients and error bars for national, Colorado, and Denver MSA itinerary subsets

One advantage of using NHTS data for itinerary analysis is the degree to which the data can be downselected to increase specificity. To increase the relevance of the empirical formula for the Denver, CO case study, the same experiment was run for only Colorado itineraries and for only Denver metropolitan statistical area (MSA) itineraries. The differences in values for the significant terms from these itinerary subsets and from the national set were minor. A comparison between the values of the significant parameters of the empirical equations from the mentioned itinerary subsets is provided in Figure 7.

GEOGRAPHICAL CALCULATION

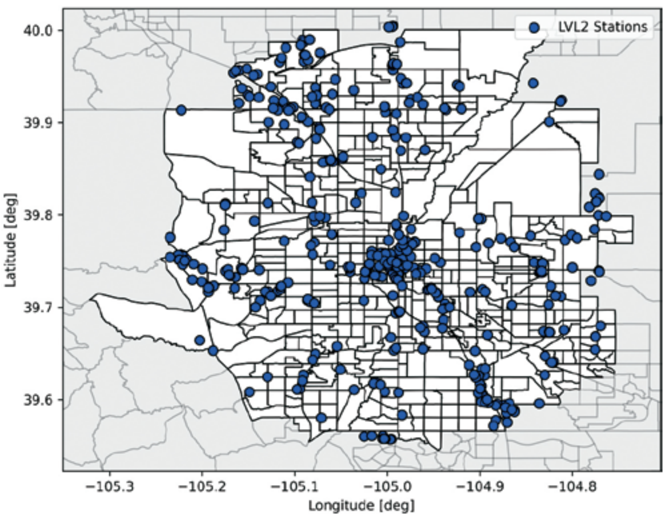
One promising application for the inconvenience score is the direct evaluation of expected inconvenience on a geographical basis. Using any desired subset of NHTS data, an empirical formula for inconvenience based on the parameters in Table 4 can be derived. Values for the coefficients can be calculated for a given geographical area using publicly available data and from this an inconvenience score can be assigned to the area. This geographical analysis allows for the visualization of location-based inequity of experience due to BEV charging inconvenience and for the direct evaluation of proposed future EVSE infrastructure in terms of its effects on BEV charging inconvenience. In this section, the methods for computing inconvenience score at a census tract level are presented using the Denver, Colorado urban area as an example.

ACS CENSUS TRACTS

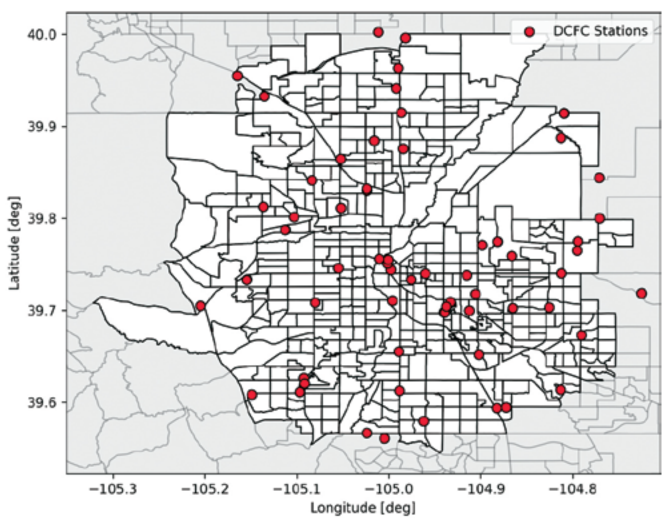
The census tracts used for the geographical calculation of inconvenience were taken from the 2019 ACS. The 2019 ACS was chosen as the ACS contains a great variety of demographic data on a census tract level and the 2019 version is the most recent complete version of the survey. In this paper, the authors defined the urbanized area surrounding Denver, Colorado to be the area within 25 km of the center of the city as plotted in Figure 8.

LOCATIONS OF EVSE INFRASTRUCTURE

The locations of existing chargers were pulled from National Renewable Energy Laboratory (NREL)'s alternative fuels data center (ADFC) (Alternative Fuels Data Center 2023). The data provided by ADFC lists the locations of publicly available as well as private chargers along with the charger category (AC level 1, AC level 2, DCFC) and other information. For this study only publicly



(a) AC Level 2 charging stations



(b) DCFC stations

Figure 9. Locations of charging stations in Denver, Colorado urbanized area

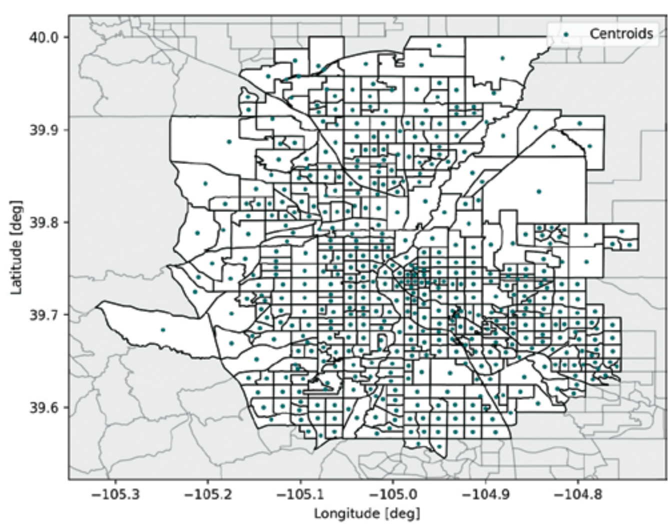


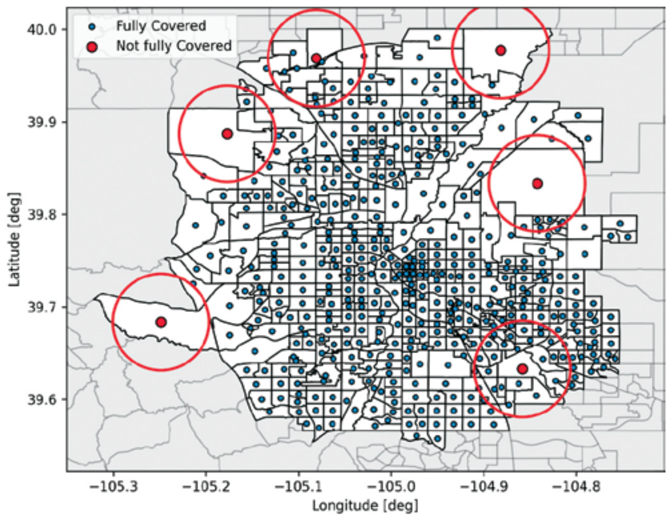
Figure 8. Denver, Colorado urbanized area census tracts form 2019 ACS

available level 2 and DCFC chargers were considered. Maps of the locations of level 2 and DCFC chargers in the Denver Colorado urbanized area are provided in Figure 9.

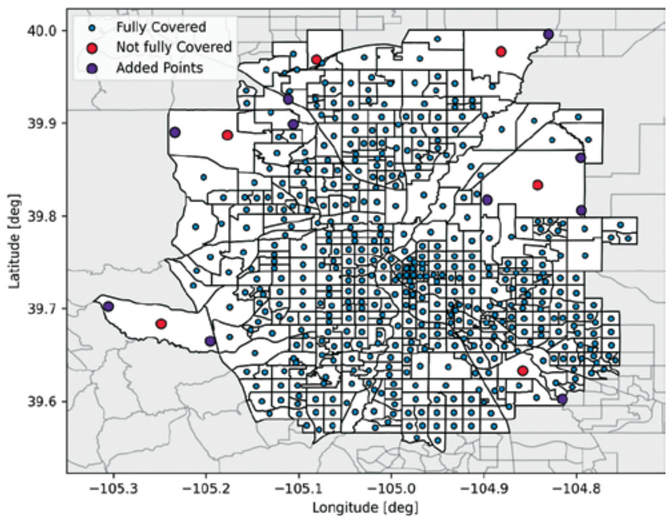
COMPUTING DCL

DCL is defined as the likelihood of finding a Level 2 charger at or sufficiently close to a given destination. Thus, to compute DCL requires knowledge of the locations of all likely destinations for a given person or geographical area. While there are a huge number of possible destinations that a person could visit in a given area, the authors propose that the only destinations that are relevant are popular long-dwell locations. The locations of popular long-dwell locations can be pulled from various mapping services such as Open Street Map (OSM) (OpenStreetMap 2023), Google Maps (Google 2023), Bing Maps (Microsoft 2022; Microsoft 2023), and others. The authors chose to use Bing Maps due to a combination of factors including the ease-of-use of the API, the quality of documentation, and pricing.

Using Bing Maps API, it is possible to pull the 25 most relevant destinations in a given category for a 5-kilometer area around a given point. The categories selected were the "Shop" category which includes the locations of major retailers, the "EatDrink"



(a) Covered and non-covered tracts



(b) Added points for destinations search

Figure 10. Census tract centroids and added search points

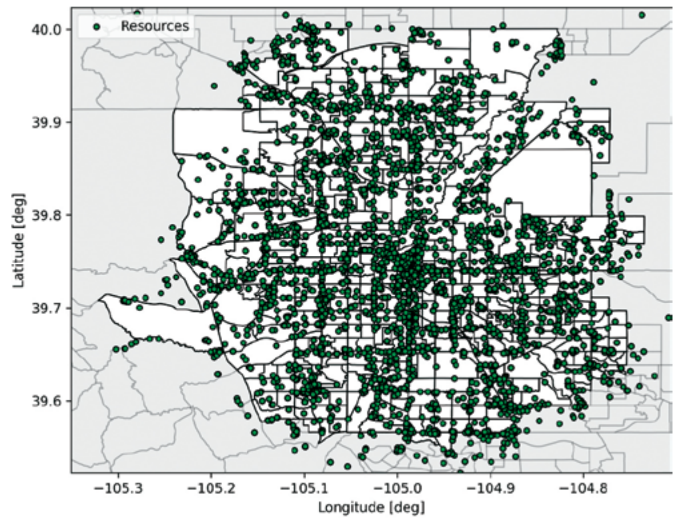


Figure 11. Locations of relevant destinations

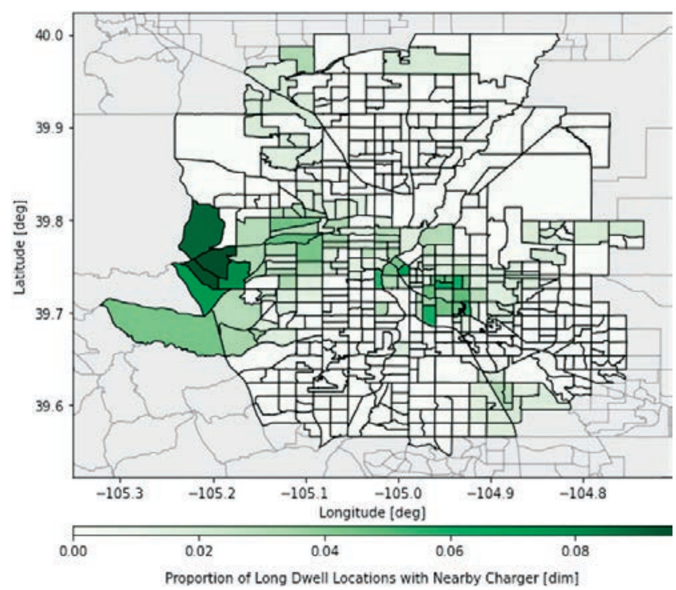


Figure 12. Census tract level DCL

category which includes the locations of bars, restaurants, and grocery stores, and the "SeeDo" category which includes the locations of entertainment venues and local attractions. Therefore, for a given census tract up to 75 popular, long-dwell destinations could be pulled based on the census tract centroid. For certain census tracts, the area covered by the centroid based search did not contain the entire tract area so additional points were added in the centroids of the non-covered areas until the whole area was covered as shown in Figure 10.

Finally, the locations of the destinations could be compared to the locations of Level 2 charging stations and those within a given distance (in this case 50 m) would be considered to have a nearby charger. Thus, for a given census tract the value for DCL would be the ratio of destinations with nearby chargers to total destinations. The locations of relevant destinations in the Denver, Colorado urbanized area and the census tract level DCL for the same area are presented in Figures 11 and 12.

COMPUTING DCFCP

DCFCP is the round-trip travel time, in minutes, to the nearest DCFC station. For a census tract this can be approximated by calculating the time required to travel from the tract centroid to the nearest DCFC station. for larger tracts this value is the average of travel times originating from added points as discussed previously. To calculate the expected travel time from a given tract centroid to the nearest DCFC station the authors used Mapbox routing (Mapbox 2023) with the trip duration being used as the travel time multiplied by two to reflect the round-trip duration. DCFCP values for the selected census tracts are given in Figure 13.

RESULTS

With census tract level DCL and DCFCP computed, S_{IC} can be plotted on a census tract level. Calculating S_{IC} or a given census tract does require assuming values for HC, WC, BC, and DCFCR. DCFCR must be assumed because charging rate information is not provided by ADFC. Census tract level values for HC, WC, BC, and DCFCR could possibly be estimated from census and other data in the future but for the purposes of this paper the same values will be assigned to all census tracts to show the impacts of the infrastructure parameters DCL and DCFCP. Unless otherwise specified the values used are those seen in Table 8.

A comparison of census tract level S_{IC} relative to assumptions about the availability of home and work charging is shown in Figure 14.

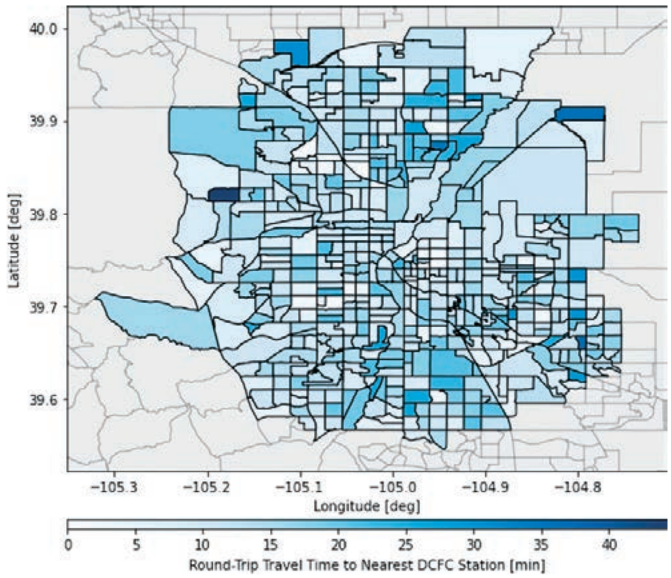
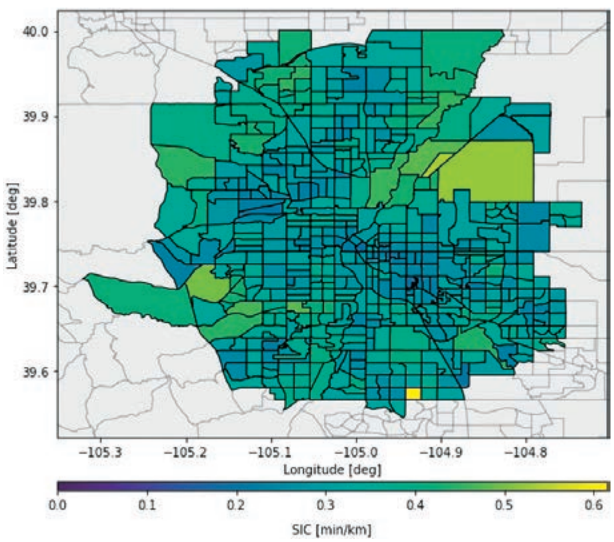


Figure 13. Census tract level DCFCP

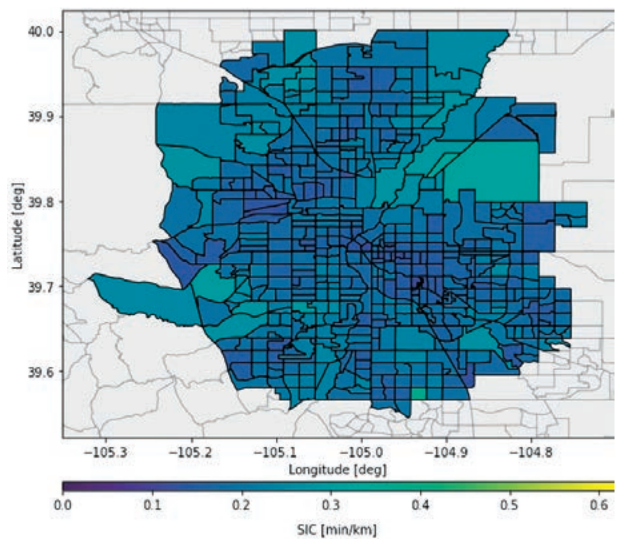
Table 8. Default values for parameters

Parameter	Levels	Unit
Home Charging (HC)	0	dim
Work Charging (WC)	0	dim
Battery Capacity (BC)	80	kWh
DCFC Rate (DCFCR)	150	kW

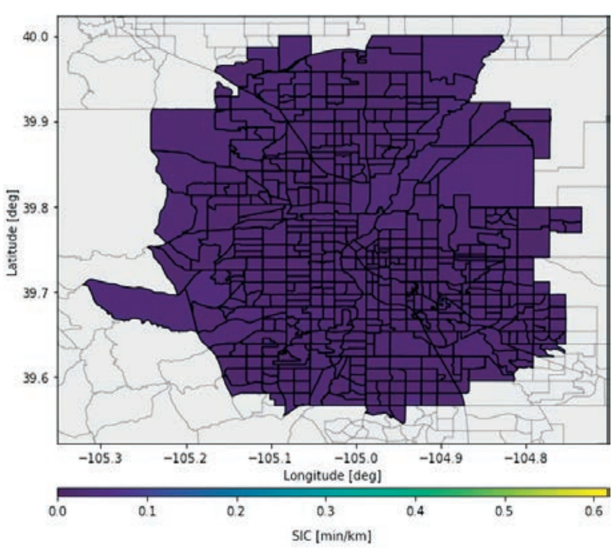
The resulting choropleths seen in Figure 14 provide real context to the empirical formulae presented earlier in this paper. What is plain is how much a BEV operator's experience will be affected by whether or not he or she can charge at home and/or work. Although disparities between the census tracts still exist, having the ability to charge at home decreases both the mean value and the standard deviation of inconvenience. Thus, those with the ability to charge at home are both better off and less susceptible to infrastructure parameters than those unable to. For those



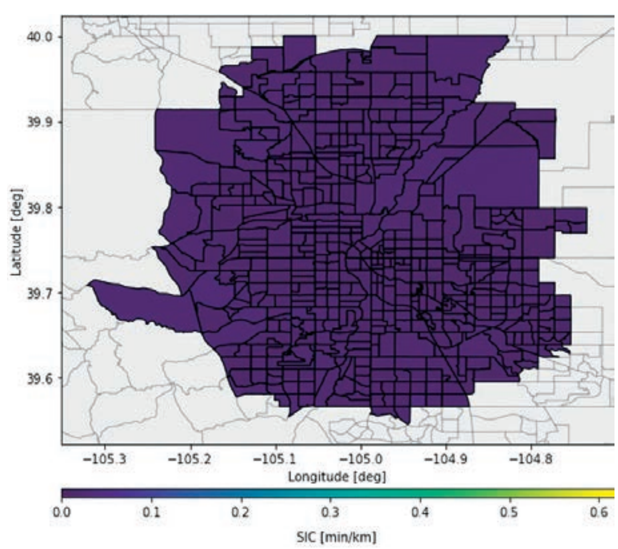
(a) HC = 0, WC = 0, $\mu_{S_{IC}}$ = 0.317315, min/km, $\sigma_{SIC,D}$ = 0.056954 min/km



(b) HC = 0, WC = 1, μSIC = 0.193744, min/km, σSIC,D = 0.03496 min/km

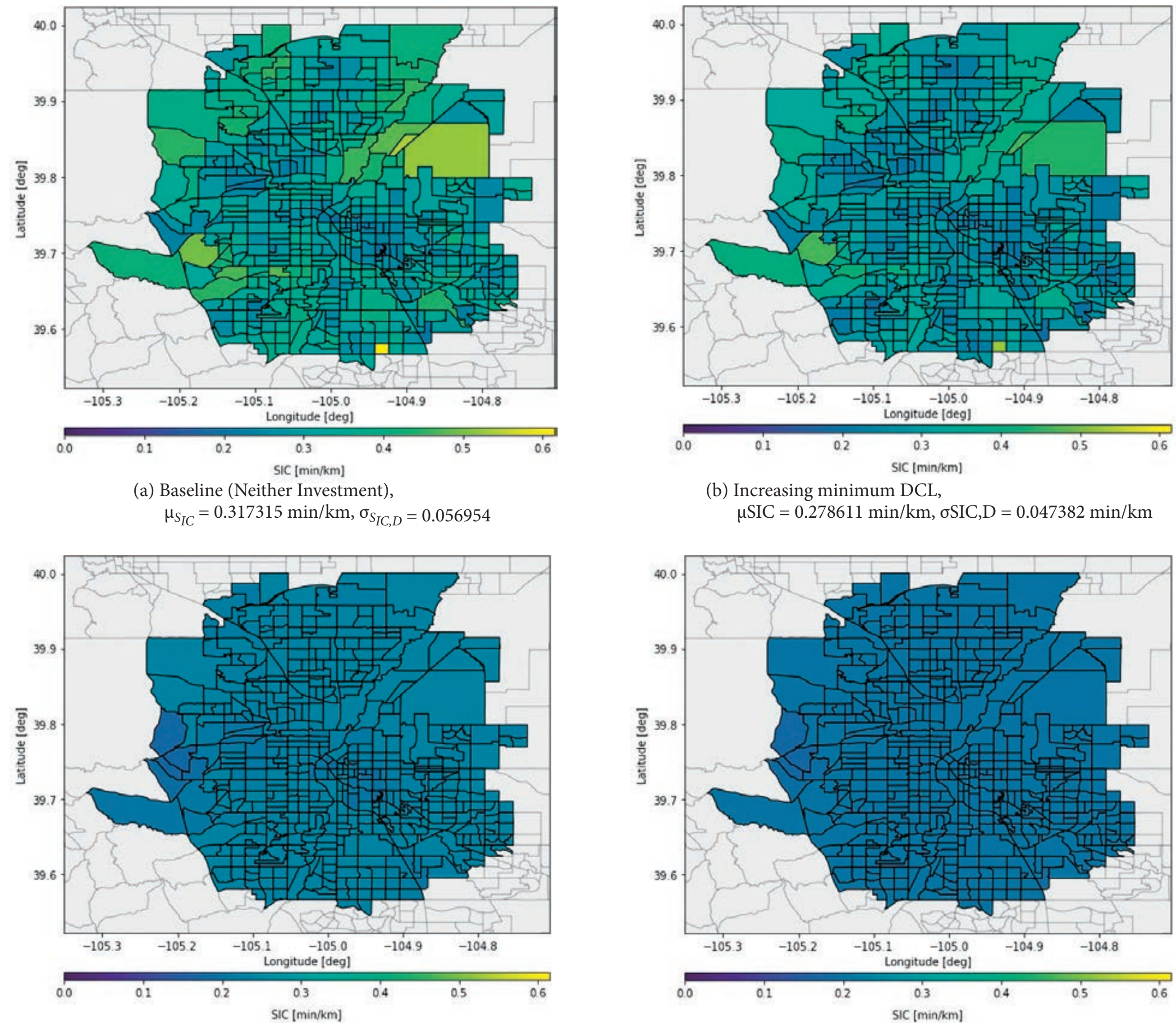


(c) HC = 1, WC = 0, μSIC = 0.020381, min/km, σSIC,D = 0.003269 min/km



(d) HC = 1, WC = 1, μSIC = 0.017014, min/km, σSIC,D = 0.003683 min/km

Figure 14. Comparison of S_{IC} for those with home and work charging available and those without



(a) Baseline (Neither Investment), μ_{SIC} = 0.317315 min/km, $\sigma_{SIC,D}$ = 0.056954

(b) Increasing minimum DCL, μSIC = 0.278611 min/km, σSIC,D = 0.047382 min/km

(c) Decreasing maximum DCFCP, μSIC = 0.230185 min/km, σSIC,D = 0.010399 min/km

(d) Both investments DCFCP, μSIC = 0.20293 min/km, σSIC,D = 0.003237 min/km

Figure 15. Effects of doubling DCL and/or halving DCFCP for no home or work charging

reliant on public infrastructure location plays an important role in determining experience. Even within the urbanized area surrounding Denver, Colorado, the amount of inconvenience experienced on a per kilometer basis can vary significantly. The distribution of EVSE infrastructure in the Denver, Colorado urbanized area is rather unequal with Level 2 chargers clustered towards the city center and in the western areas of the city and DCFC stations located close to the highways. Therefore, one should not be surprised to find a resulting geographic inequity of experience due to inconvenience.

DISCUSSION

It should be no surprise that home and work charging are such powerful factors in determining BEV operational inconvenience. The importance of home charging was identified by the authors in a previous study (Rabinowitz et al. 2023a) which used a different dataset and slightly different methodology but came to roughly the same answers. Home charging is the foundational element in the charging pyramid model that has dominated thought on BEV charging in the past with work charging being the next element. The results of this paper more or less validate the descriptive quality of the charging pyramid model for the current state of EVSE infrastructure in a typical US city. If one cannot charge at home or at work the charging pyramid model is invalid for him or her.

Those most able to charge at home, and thus most able to operate a BEV, are also likely to be among the richest of Americans. Poorer demographics will probably not simply accept a massive time burden as an inevitable cost of BEV ownership. There is the possibility that, independent of economic incentives, poorer Americans will continue to buy new or used ICVs and run their vehicles for longer because of the inconvenience associated with BEVs. In addition to the moral issues inherent in any large inequity, the inequity in BEV operational experience due to charging may very well delay or limit BEV adoption and thus threaten emissions goals in the future. With this in mind, it is worth asking how infrastructure could be developed in order to minimize the inequity of experience between those who can charge at home and those who cannot.

Policy makers looking to address the inequity in BEV operational experience should consider what are the relative merits of investment in high-rate charging vs low-rate charging. As a point of discussion, suppose that an investment could be made such that the DCL for all census tracts were raised to be at least half of the current maximum value. Alternately an investment could be made which would reduce the DCFCP of each tract to no higher than twice that of the current minimum value. Figure 15 shows how the S_{IC} maps change due to these investments.

Although likely expensive, both investments should be feasible as, inherently, as the required minimum and maximum levels are already achieved in many census tracts. Of the two investments, reducing the maximum DCFCP is clearly the more impactful. The combination of both investments would bring the mean and standard deviation of inconvenience down into the range seen for the work charging enabled scenario in Figure 14. More investment would be needed to get into the range of the home charging enabled scenario.

CONCLUSIONS

For a successful green transition to take place in the American transportation sector, the majority of Americans must decide to purchase or lease BEVs for personal transportation. Operating a BEV will always be easier for those with the ability to charge at home and/or work; currently, under-developed EVSE infrastructure exacerbates this inequity of experience. In order to effectively solve the issues with current EVSE infrastructure a quantitative understanding of charging inconvenience and the factors which underlie it must attain. In this paper a novel method for computing expected BEV operational inconvenience due to charging on a geographical basis is presented. This method allows for quantitative assessments of the impacts of potential EVSE infrastructure investment based on locations and types of chargers. The quantitative metric, inconvenience score (S_{IC}), which can be computed for specified demographics and geographical regions using only publicly available data should be considered as a performance metric in future EVSE infrastructure analyses. ■

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Carbon Considerations for Systems Evolution

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ABSTRACT
In the early stages of systems development, systems engineers will typically evaluate alternatives based on performance, cost, risk, and schedule to evaluate the solution space of alternatives. While these criteria have proven to be successful, there is growing interest in the analysis of carbon costs as well to contribute to the decision making. These decision criteria are very good to help the decision maker select the best alternative within the solution space in which to develop a system concept. We offer another criterion for consideration to account for carbon expenditure throughout the systems engineering lifecycle. We believe that including this dimension can influence decision makers to evaluate a richer portion of the solution space. This approach is developed and exercised with a notional example.

INTRODUCTION

Systems concepts during the conceptual development phase are often evaluated in terms of performance, cost, and schedule, particularly when evaluating different alternatives for moving to the development phase. With the growing interest and concern of emissions to affect the entire planet, this paper takes motivation to introduce a new aspect for considering system concepts, with a carbon count. There are several ways to examine counting carbon, be it at the manufacturing, or operations level. We introduce a new perspective for systems engineers and program analysts to consider when developing system concepts that would be often considered within an analysis of alternatives (AoA). We perform a literature review on the ways to consider carbon emissions as well as integrating into an AoA-type format for decision makers.

LITERATURE REVIEW

Our first part of the literature review explores a systems engineering analysis and decision-making framework that can support the consideration of carbon emissions early during the systems engineering lifecycle.

INCOSE's model-based systems engineering (MBSE) initiative (INCOSE 2022) has been driving toward implementing MBSE practices across the whole lifecycle, including in the concept stage. The benefits of MBSE are well published, with Henderson & Salado (2020) identifying a list of measured, observed and perceived benefits, including better communication and information, increased traceability, and better accessibility of information. It is an information framework, realized in a schema, that supports the MBSE benefits Henderson & Salado identify.

In 2008 Robinson et al. (2010) explored the application of MBSE to a real acquisition project in the concept stage, within the Australian Department of Defence. This exploration showed that a model-based conceptual design (MBCD) approach was "completely compatible with current mandated (document-centric) capability development processes." Key to the success of this project, was the clear definition of the schema underpinning the MBCD approach. This early definition of the concept stage schema has been expanded since to include information classes such as risk (Cook et al. 2015) and the test domain (Flanigan and Robinson 2019). Flanigan and Robinson (2020) demonstrated how a MBCD approach, with a robust schema, can be employed to better consider resilience in the concept stage with alignment to an analysis of alternatives (AoA) approach defined in the AoA Handbook (US Air Force 2017). The MBCD schema, described by Flanigan and Robinson (2020), potentially provides the information framework for introducing a new carbon-counting perspective for systems engineers and program analysts, to better inform decision makers within the Analysis of Alternatives approach.

Our second part of the literature review looks at the different government organizations concerns on carbon emissions reductions and goals. These may assist the analysis of our case study.

The United States Department of Defense (DoD) (September 2021) considers climate change in their climate adaption plan, particularly how systems are developed. Specific US military services have published their strategies and goals on how to address climate change and reduction in the carbon footprint goals (DoD September 2021, DoD October 2021, Department of the Air Force 2022, Department of the Army 2022, Department of the Navy 2022). The United Nations and other countries also have identified carbon reduction goals (UN 2015, UN 2022, Commonwealth of Australia 2022) which range from improving vehicle efficiency to reducing certain elements during system development to implementing activities to reduce the overall global average temperature.

Other research has been performed to calculate the carbon footprint of components (Wang 2022, Yung et al. 2018, Gupta et al. 2022, Williams et al. 2002) and add these calculations along with other aspects of the systems engineering lifecycle to account for the overall carbon count. Müller et al. (2020) considers raw material manufacturing, component production, system integration, system testing, system usage, system maintenance, and system retirement as some of the key activities to consider when accounting for carbon. Mathers et al. (2014) provides estimates of carbon footprint per mile depending on the mode of transportation and weight of material carried, some of the modalities include air, ship, rail, and truck. As there are numerous options to construct the system, the analyst should be cognizant to understand the scope of analysis when considering carbon counting: do we count all the way back to when extracting materials out of the ground, when the components are already manufactured, or when the final system has been integrated?

When asked to evaluate the solution space between multiple system alternatives, systems engineers will typically perform an analysis of alternatives (AoA). Typical criteria are performance, cost, schedule, and risk. We find that the decision analysis approach can be applied to multiple parts of the systems engineering lifecycle (technical planning, technical assessment, stakeholder requirements, requirements analysis, and architecture design) (DoD 2022). NASA (2020) also has a similar decision analysis approach to identify parts of the lifecycle (mission concept, system requirements, mission definition, system definition, preliminary design review, critical design review, production readiness review). The US Air Force (USAF 2017) has an Analysis of Alternatives (AoA) Handbook that describes several integrated product teams (IPT) to focus on alternatives, effectiveness analysis, cost analysis, and risk assessment, as well as comparing alternatives, evaluating differing costs, capabilities, and risks. It is here where we can draw some motivation to include carbon footprint as well. Systems engineering textbooks (Kossiakoff et al. 2020; Buede and Miller 2016) contain additional information regarding lifecycle models as well as decision criteria.

APPROACH

We will revisit the systems engineering lifecycle and model based conceptual development (MBCD) framework, performed in previous work (Flanigan and Robinson 2019, 2020, 2021, 2022) to evaluate how conceptual design systems engineering can be applied to the problem in the operational, systems, and testing domains. We believe that the MBCD framework is still valid for this approach, with some modifications applied to the framework.

Systems Engineering Lifecycle

The systems engineer works across the entire lifecycle of the system being engineered. From the concept stage to the retirement of the system, the systems engineer must coordinate the lifecycle activities to ensure that risks are managed, opportunities are explored and ultimately a successful system in delivered, deployed and retired (Walden et al. 2015). However, this lifecycle, and the changing nature of systems, is being questioned by the challenges that society needs to address. As we are all painfully aware, climate change and exploitation of earth's finite resources are one of our most serious challenges that needs solving. Systems engineers must meet that challenge.

Highlighted in the United Nations sustainable development goals (SDGs) (United Nations 2022), the climate action goal calls for us to "Take urgent action to combat climate change and its impacts". To address this, INCOSE responded in its Systems Engineering Vision 2035 (INCOSE 2022) to challenge systems engineers to "help bring about informed overarching system solutions to climate change which include changes in public policy with coordinated and actionable mitigation steps that influence societal, corporate, and individual behaviors." This paper aims to contribute to that cause by considering how the systems engineering lifecycle can be improved to better act on climate change.

If we are to successfully reduce the carbon footprint of the systems we deliver, deploy, and retire, then the "carbon cost" of each stage of the lifecycle must be challenged. As we know, the projects that spend the greatest proportion of their resources in the concept stage are likely to be the most successful (Honour 2011). If the future systems to be engineered are to have a reduced carbon footprint, and reduce their impact on the environment, then understanding what can be achieved in the concept stages is surely going to lead to the greatest success.

A well-executed concept stage should provide immediate opportunities for reducing the carbon footprint of the system being engineered, with those opportunities flowing downstream through the remaining stages of the lifecycle. Within the systems engineering body of knowledge there have been many advances in the delivery of the concept stage (Robinson, Waite, Do 2014), but there are none known to the authors that have explicitly focused on developing opportunities that lead to reducing the carbon footprint. The concept stage is

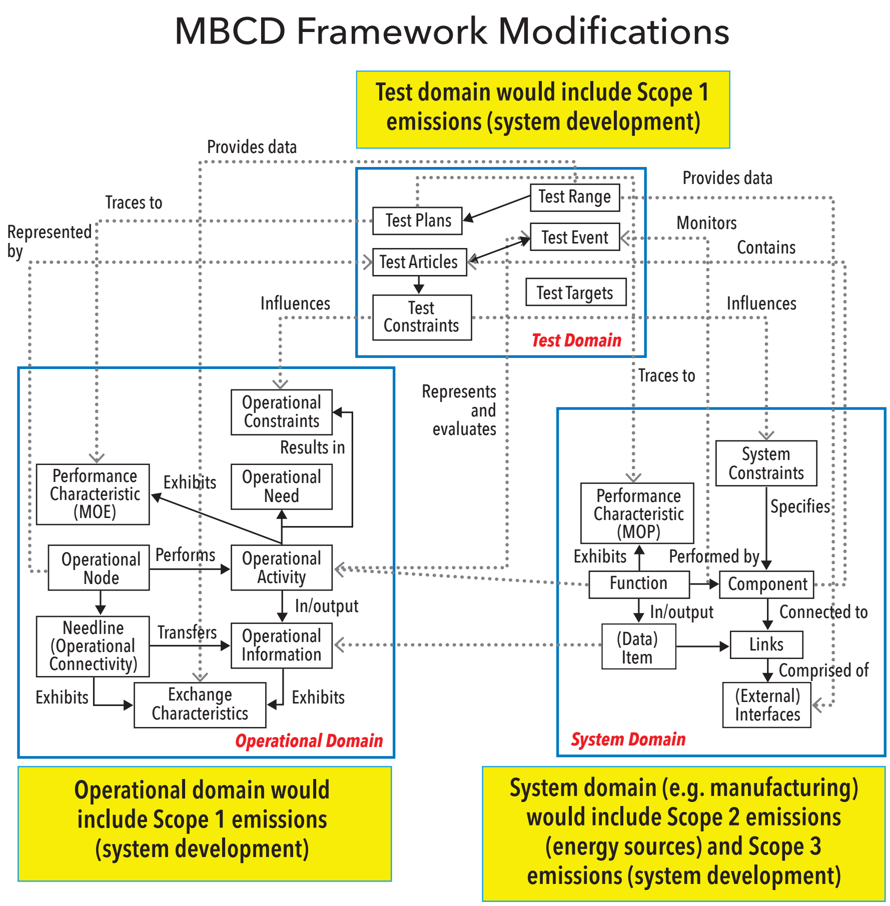


Figure 1. MBCD framework modified for carbon counting

focused on developing the stakeholder needs and requirements, reducing risks, pursuing opportunities, and defining the concepts of use (Walden et al. 2015). All these artifacts should set the project vision for reducing the carbon footprint of the system when considering delivery, deployment, and retirement. For this paper, the authors have chosen to explore the development and definition of the concepts of use, through model-based conceptual design approaches (Robinson, Waite, Do 2014).

MBCD Framework, Revisited

We revisit the MBCD framework as described to evaluate the changes to consider carbon factors. Figure 1 provides an updated view of the framework with discussion on how it could be modified for our analysis purposes.

Examining the MBCD schema, Figure 1, we can see that many of the systems engineering information classes captured in the schema can be considered to influence the carbon cost of a system being delivered, deployed, and retired. Key is the systems usage, as identified by Sparrevik and Utstøl (2020), as Scope 1 emissions, compared to Scope 2 (as a result from purchased energy sources), and Scope 3 emissions (development of systems). In the MBCD schema the 'operational activity' is the key information class to understanding the usage of a system, and therefore the highest cost of carbon pollution from energy sources.

The system engineer can make design choices between different solution options, based on the carbon cost to develop the component, however, to estimate the carbon cost across the full lifecycle carbon cost, the concept of use must be analysed for alternative solutions. This is described through the 'operational activity' information class in the model. For example, a single component may have a high individual development carbon cost (Scope 3), however if it provides an enhanced usage performance then it may pollute less carbon due to its efficient use (Scope 1). Conversely a low development carbon cost component (Scope 3) may have high pollution usage cost due to its poor performance and therefore inefficient use (Scope 1).

In this paper we explore the AoA approach to make carbon-cost design choices during the conceptual design of the operational activities, that are then realized through system concepts.

NOTIONAL EXAMPLE

We will describe our approach towards a notional example of surveillance of forest fires, such as in a national park, to support the command and control of bushfire response options. The size of the park is so large that the concept may require a multi-layered approach for adequate and timely detection and monitoring of the fires. Several alternatives are identified to produce notional analysis for the decision makers to consider.

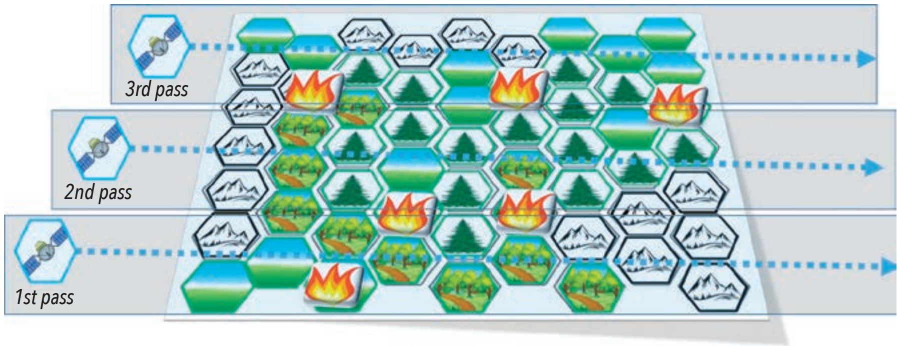


Figure 2. Satellite alternative coverage of national park

System Concept Alternatives

For this example, we have three separate alternatives. The first is a satellite-based system that can provide a frequent revisit surveillance capability on the park and has broad coverage. The satellite orbit is not easily or quickly changeable, so the park coverage is based on the orbit revisit rate. The satellite will not have great resolution into a specific area of the park. The satellite is (relative to other alternatives) very expensive to launch, operate, and maintain. This sensor is normally operated as a single system for the park example. Figure 2 provides an example of the satellite coverage.

The second alternative is an airborne system, such as a crewed aircraft or uncrewed aerial system (UAS). This provides a mobile surveillance capability that can be rapidly reassigned to different parts of the park and can provide a detailed view into specific areas. The airborne system is slower (relative to the satellite) and will take some time to build a complete picture of the park and the fire status. The airborne system is moderately expensive to operate and maintain. This sensor is normally operated in a single system configuration, with several other airborne systems available for maintaining a higher availability. Figure 3 provides an example of the airborne system coverage.

The third alternative is a series of ground-based sensors to provide a very detailed view of the ground conditions. This alternative is fixed (so cannot expand any coverage of the park on its own) and may be relocatable by personnel. These sensors are normally pre-established in some form of pattern across multiple geographically dispersed locations to provide some indications and warning of the fire condition. This sensor is the least expensive to operate and maintain. Figure 4 provides an example of the ground sensor coverage.

For the purpose of this example, we develop a set of utility functions for the three alternatives for specific criteria to consider. These are: wide area surveillance, detailed surveillance, relocatability,

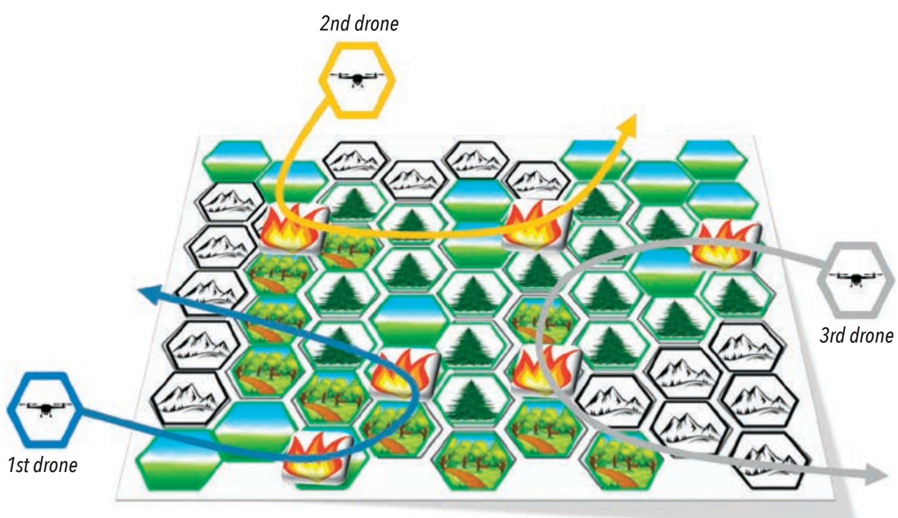


Figure 3. Airborne alternative coverage of national park

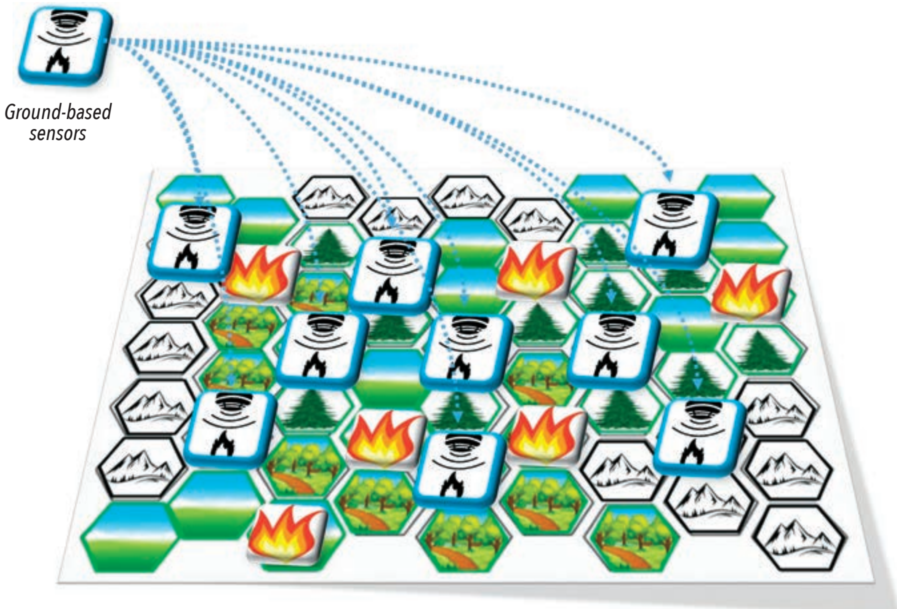


Figure 4. Ground based sensors alternative coverage of national park

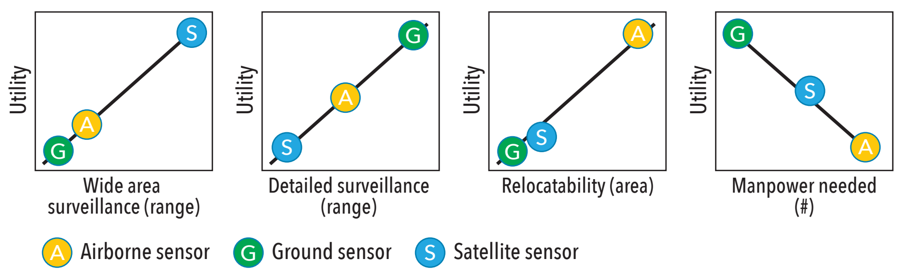


Figure 5. Fire sensing alternatives utility functions

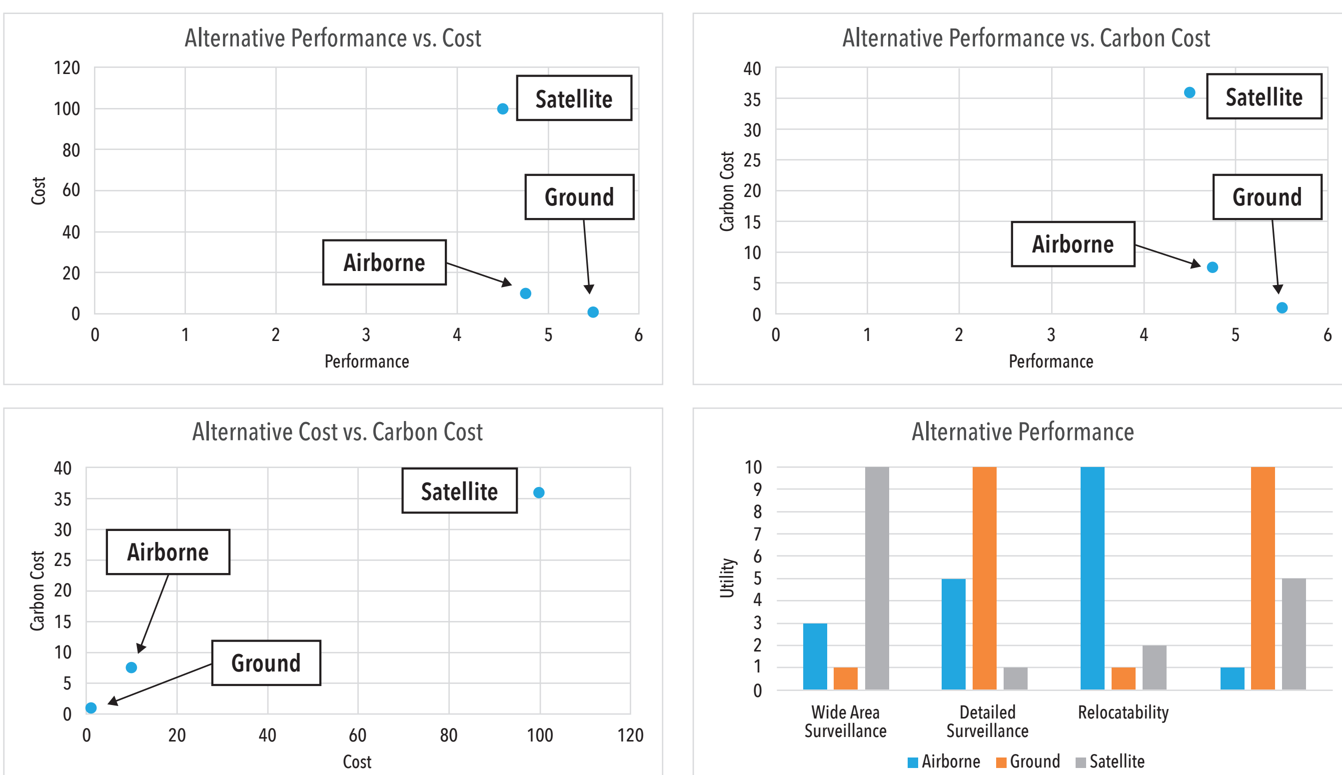


Figure 6. Alternative performance charts

manpower needed for operations, cost, and carbon emissions. Figure 5 provides an example of the first four of these utility functions and the systems.

Using these utility functions and analysis principles, we can develop notional performance values for each of the alternatives, assuming that each of the criteria are weighted equally. We will also utilize the calculations given in Mathers et al. for estimating the carbon costs of the alternatives, and satellite estimates from Segert (2021). We may be able to describe these alternatives to decision makers as found in Figure 6, with performance in the bottom right quadrant. Note that each of these values are the average of a high and low alternative. The other three plots look to evaluate the criteria of performance, cost, and carbon cost.

Alternatives Analysis

This can describe other areas to analyze the alternative solution space, as shown in Figure 7. The figure on the left can indicate the optimal path given a starting point (open triangle) and to visit each fire location, given the nearest location, and subsequently finding the next nearest location. If there are constraints on airborne system endurance, then a fleet of airborne systems would be required, as the figure on the right indicates to show 3 systems are needed (if 300 minutes are the limit for each system).

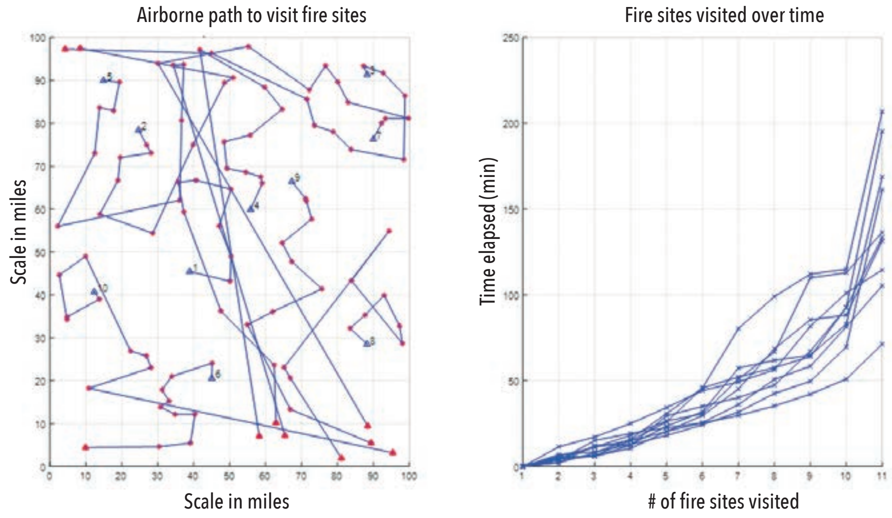


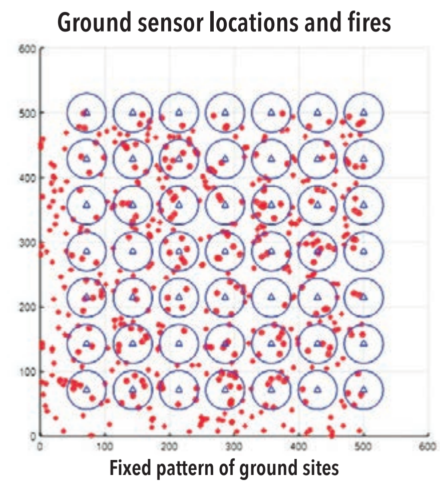
Figure 7. Airborne-based flight path and fire detections

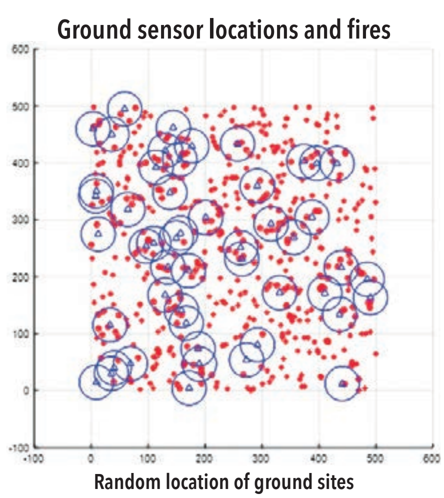
During a trade study, we may consider different aircraft patterns (random vs. ladder-search pattern vs. other search patterns) to see if there are differences in fire detection performance, cost, and carbon cost. We may also consider varying the number of aircraft and then evaluate the metrics. Although we increase the number the aircraft to shorten the time to detect all fires, we expect to increase the cost and carbon costs, which would be a tradeoff by the stakeholders.

Ground sites are distributed throughout the park and have an effective range. If there are constraints on the number of ground sites, or variability in detection range, then this performance may change. See Figure 8 for an example visual of the fire locations and sensor layout, as well as the cumulative detections. This figure provides two examples of ground sensor deployment – the figure on the left is a fixed pattern, while the figure in the middle is a random pattern. During a trade study, we may consider different placements of the ground sites to include random, perimeter, or checkerboard patterns, and determine how well each of the options may vary in terms of fire detection performance, cost, and carbon cost. Like the aircraft example, the employment of the sensors would be a consideration in the tradeoff decisions by the stakeholders.

Satellites have an effective "block" or "swath" of sensor range. The number of fires can then be collected within each of the blocks, visualized in a horizontal orientation. In this example, Figure 9 shows a visual of the 3 horizontal blocks from 3 notional satellite passes, and the cumulative detections within each block. Like the other alternatives, we would expect the larger number of satellites would improve performance at the detriment of cost and carbon cost and would be a consideration in the tradeoff decisions by the stakeholders.

To help categorize the analysis of alternatives, we can consider a simple 8-unit cube. Depicted in Figure 10, the traditional metrics of performance and cost are on





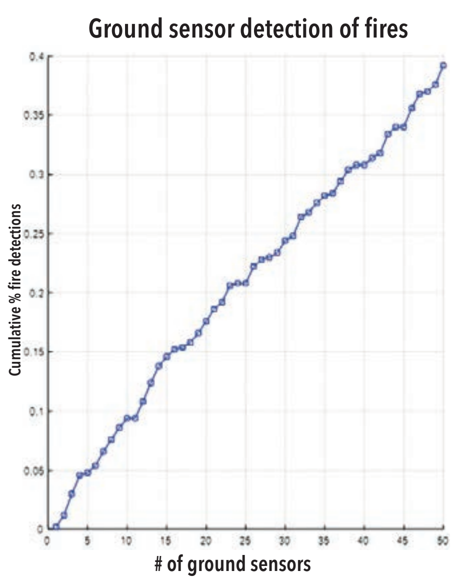


Figure 8. Ground-based sensor locations and fire detections

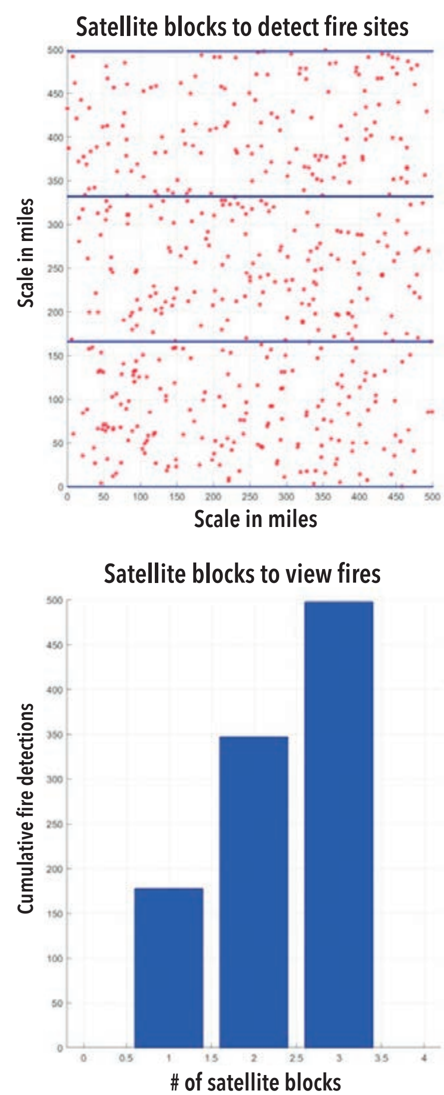


Figure 9. Satellite-based sensor blocks and fire detections

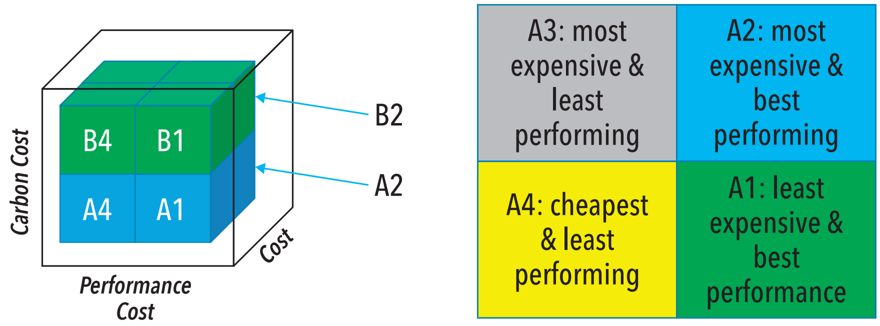


Figure 10. Quadrants in the carbon cube

the horizontal axes, with carbon cost on the vertical. The goal being to develop the concept of use for each solution options such that they best system appear in the A1 quadrant, being the least expensive, best performing, and lowest carbon cost. The carbon costs are intended to be in two levels, the A-level (bottom) has the lower carbon cost, and the B-level (top) has high carbon values.

To analyze the alternatives, we do a simple experiment with varying the numbers of nodes for each solution class, and therefore their concept of use. For the aircraft we increase numbers from 1 to 10 to surveil the entire park. The cost and carbon costs increase linearly with each added aircraft, while the performance shows an increased value with each additional aircraft in the problem.

Figure 10 provides a view of the performance vs. cost vs. carbon cost with increasing aircraft. We can see that it shifts rapidly from the A4 quadrant to the A3 quadrant with increasing aircraft and could extrapolate based on the points that it would eventually reach the A2 quadrant with more aircraft. For the satellites, it rapidly shifts from the A4 to A2 quadrant, but at a high cost (vertical axis). For the ground sensors, it starts slowly in the A4 quadrant, and will eventually reach the A2 quadrant with a larger number of systems. Given this image of performance vs. cost vs. carbon costs, decision makers may opt for a mix of systems and their capabilities to reach the performance, cost, and carbon cost goals. By plotting the goals into the quadrants, as shown in Figure 11, we can identify where future improvements can be made.

SUMMARY

We can demonstrate from our notional example that analyzing the carbon cost due to the concept of use can play a significant impact in the selection of alternatives, and through the analysis of the problem, can identify where certain alternatives may or may not meet our respective goals. Prioritization of the criteria can be performance with decision analysis techniques such as analytic hierarchy process (AHP) or rank ordered centroid (ROC), with weighted sums to gather performance and charts to show cost-effectiveness (or now carbon-effectiveness or carbon-cost) comparisons can be made.

The solution classes and concept of use were captured as operational nodes and operational activities, respectively, in the MBCD schema. The employment of the MBCD schema has been kept at the simplistic level to demonstrate the viability of such approach in developing a conceptual design of the solution system. Complexity of the model-base representation should be increased in a full analysis of alternatives to explore the full mission, logistical support, and other such operational activities required to deploy a capability.

This simplistic study helps start the transition towards systems engineers better considering the impact of carbon emissions, and ultimately environmental impact in the design of new capabilities and delivering the environmental goals of Systems Engineering Vision 2035 (INCOSE 2022) that INCOSE, and society more broadly, desperately needs.

NEXT STEPS

We limited our research to explore the carbon cost during the use of the capability (Scope 2), and only for a small excerpt of a mission scenario. We recommended that the next steps should expand the scenario to be more holistic and representative and consider the carbon cost across the remain two emission scopes of development (Scope 3) and direct energy (Scope 2). This would then give a clearer, more

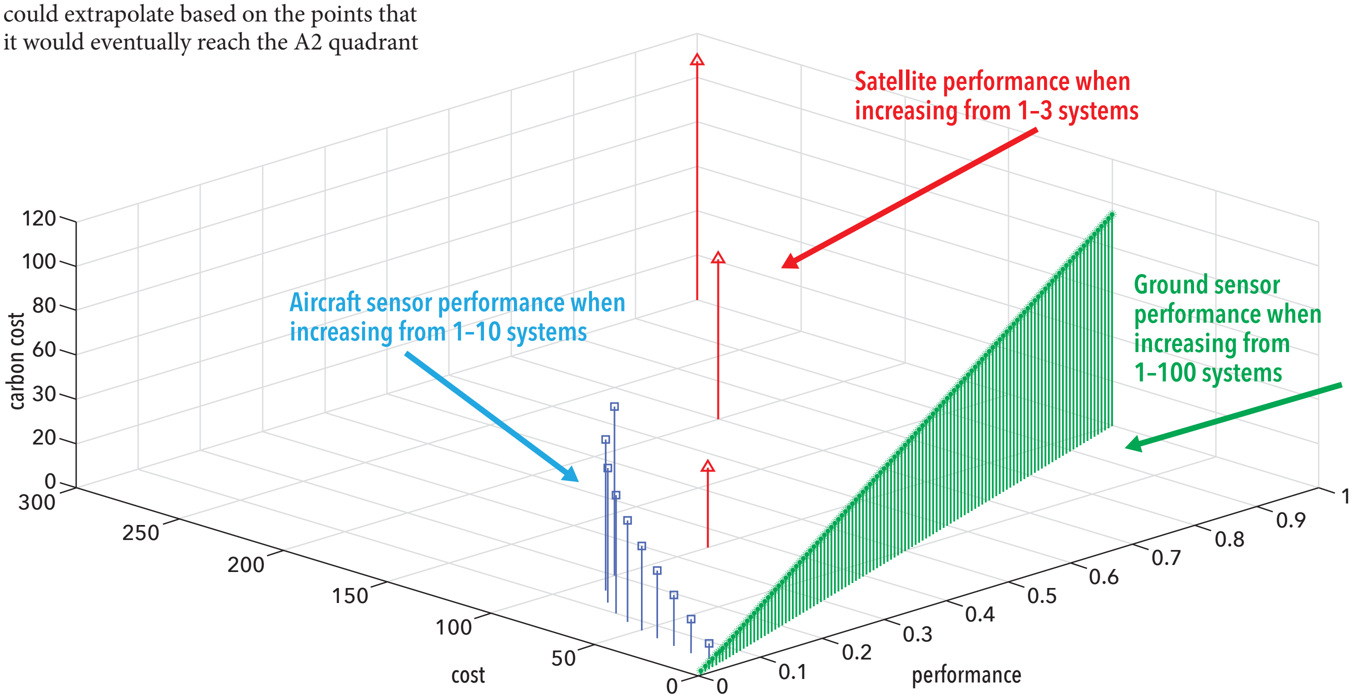


Figure 11. Example performance vs. cost vs. carbon cost plots

definitive conclusions made during the concept design phase and the analysis of alternatives study.

As we've shown the first steps towards considering different criteria for consideration, we could also look at different fidelities of simulation to consider carbon costs more accurately, particularly as operations get more complex and detailed. We may also consider different parts of the lifecycle to evaluate the creation of the systems vs. system operations vs. system retirements. Another approach could be considering the recycling costs and impacts to the system performance.

The MBCD schema provided the framework to focus the approach of assessing the carbon cost of alternative solution options. We hypothesis that further research would increase clarity on how carbon cost could be better represented in the schema, beyond a measure associated with the operational node and activity in the schema, to aide decision makers. For example, the risk of environmental impact through carbon emissions could it be identified in the schema as a risk. Risk identified in the concept stage is traditionally only consider as technical, performance, cost, or schedule risk. Alternately, given the financial evaluation of carbon emissions becoming prevalent in society, the cost of carbon emission could form part of the mission costs. ■

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> continued on page 60

Systems Engineering: The Journal of The International Council on Systems Engineering

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The *Systems Engineering* journal is intended to be a primary source of multidisciplinary information for the systems engineering and management of products and services, and processes of all types. Systems engineering activities involve the technologies and system management approaches needed for

- definition of systems, including identification of user requirements and technological specifications;
- development of systems, including conceptual architectures, tradeoff of design concepts, configuration management during system development, integration of new systems with legacy systems, integrated product and process development; and
- deployment of systems, including operational test and evaluation, maintenance over an extended life-cycle, and re-engineering.

Systems Engineering is the archival journal of, and exists to serve the following objectives of, the International Council on Systems Engineering (INCOSE):

- To provide a focal point for dissemination of systems engineering knowledge
- To promote collaboration in systems engineering education and research
- To encourage and assure establishment of professional standards for integrity in the practice of systems engineering
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The journal supports these goals by providing a continuing, respected publication of peer-reviewed results from research and development in the area of systems engineering. Systems engineering is defined broadly in this context as an interdisciplinary approach and means to enable the realization of successful systems that are of high quality, cost-effective, and trustworthy in meeting customer requirements.

The *Systems Engineering* journal is dedicated to all aspects of the engineering of systems: technical, management, economic, and social. It focuses on the life-cycle processes needed to create trustworthy and high-quality systems. It will also emphasize the systems management efforts needed to define, develop, and deploy trustworthy and high quality processes for the production of systems. Within this, *Systems Engineering* is especially concerned with evaluation of the efficiency and effectiveness of systems management, technical direction, and integration of systems. *Systems Engineering* is also very concerned with the engineering of systems that support sustainable development. Modern systems, including both products and services, are often very knowledge-intensive, and are found in both the public and private sectors. The journal emphasizes strategic and program management of these, and the information and knowledge base for knowledge principles, knowledge practices, and knowledge perspectives for the engineering of systems. Definitive case studies involving systems engineering practice are especially welcome.

The journal is a primary source of information for the systems engineering of products and services that are generally large in scale, scope, and complexity. *Systems Engineering* will be especially concerned with process- or product-line–related efforts needed to produce products that are trustworthy and of high quality, and that are cost effective in meeting user needs. A major component of this is system cost and operational effectiveness determination, and the development of processes that ensure that products are cost effective. This requires the integration of a number of engineering disciplines necessary for the definition, development, and deployment of complex systems. It also requires attention to the lifecycle process used to produce systems, and the integration of systems, including legacy systems, at various architectural levels. In addition, appropriate systems management of information and knowledge across technologies, organizations, and environments is also needed to insure a sustainable world.

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Model-Based Framework for Data and Knowledge-Driven Systems Architecting Demonstrated on a Hydrogen-Powered Concept Aircraft

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ABSTRACT

Aircraft development is a protracted process over many years. Novel concept aircraft with new energy sources and disruptive systems technologies are investigated during the aircraft conceptual design phase with the goal to achieve sustainable aviation. Current development cycles need to be accelerated to reduce time to market and development costs of novel aircraft, while still handling complexity and uncertainty of systems technologies. Therefore, a holistic framework for knowledgebased systems architecting using a model-based systems engineering approach is presented. This framework has the purpose to conserve and provide knowledge, that is, information, data, and experiences about existing systems architectures, to the engineer. The developed framework consists of a database concept, a method for model-based systems architecting, and an interface to the overall systems design software tool *GeneSys*. Based on evaluating different modeling languages and tools, *MathWorks System Composer* is selected as most suitable tool for knowledge-based systems architecting. The developed framework is then demonstrated by conserving and reusing formalized knowledge for the design of a novel hydrogen-powered concept aircraft. On-board systems architecture models are saved in a database and automatically recreated reducing development time. The complete graphical representation could not yet be stored in a formalized manner partly reducing the advantage of a clear representation of model-based systems architecting. However, this did not reduce automatic recreation and evaluation capabilities.

INTRODUCTION

With the awareness of effects of climate change, incentives are created to reduce greenhouse gas emissions. Since the aviation industry has a significant contribution to worldwide emissions, targets for reducing emissions in this sector have been defined by the European Union within *FlightPath 2050* (European Commission 2011). To achieve these goals, a continuous evolutionary improvement of currently used propulsion and system technologies will most likely not be enough. Therefore, extended research on disruptive technologies and concepts is performed (Air Transport Action Group 2021).

As one concept, hydrogen-powered fuel cell systems (FuCS) are currently investigated, promising greenhouse gas emission free operations if hydrogen is produced based on renewable energy. FuCS deliver electric power, water, and oxygen deficient air. However, they do not provide bleed air, which is compulsory for the conventional environmental control system (ECS) and the conventional de-icing system. This demonstrates that integrating novel technologies and concepts affect the aircraft and its on-board systems (OBS) architecture based on system interdependencies. Therefore, emerging interdependencies need to be identified and assessed during the aircraft conceptual design phase to enable fast development of feasible OBS architectures (Kuelper et al. 2022).

During conceptual design many combinatorial solutions are conceivable based on a vast design space with little validated design information (Judt et al. 2016). Therefore, it is necessary to handle uncertainty and complexity (Dano 2022). Furthermore, decisions during this phase influence most of systems costs (Geiger et al. 1996). Aircraft conceptual design includes the definition and evaluation of systems architectures (systems architecting), that is, system components based on a preliminary technology selection and their interrelations, as well as preliminary systems design to perform concept studies to optimize systems architectures (Bielsky et al. 2023, Kuelper et al. 2022).

Existing architectures based on conventional technologies have been optimized in the last decades (Fuchs et al. 2021) by, for example, increasing the electrification using an electric ECS and electric de-icing system. Since numerous aircraft using these technologies are already in operation, detailed knowledge, that is, information, data, and experiences about existing OBS architectures and technologies, is available. It can be used as a foundation for development of novel concept aircraft and systems architectures (Zheng et al. 2021). Knowledge is commonly available as literature or technical documentations in an unorganized, non-machine-readable form. Furthermore, experts gain knowledge based on experiences. If experts leave an organization, loss of knowledge poses a challenge (Quintana-Amate et al. 2017). Due to demographics of western societies, retiring of experts and lack of young engineers is a challenge for knowledge management. To prevent that insights about past developments are lost and that new developments start from scratch, knowledge needs to be organized, formalized, managed, and made accessible for reuse (Page Risueño et al. 2019). Furthermore, application of knowledge-based methods by providing existing knowledge to the engineer poses a promising approach to also handle systems complexity (Pfennig 2012).

An identified suitable approach for these aspects in the context of systems architecting is model-based systems engineering (MBSE) (Bussemaker et al. 2022). MBSE is a holistic, formalized, and interdisciplinary approach for the development of complex systems based on models for requirements, design, analysis, verification, and validation while also enabling model reusability and executable specifications for a deeper understanding of a system (Fuchs et al. 2022, Object Management Group, Nowodzienski et al. 2022). Even though, model-based approaches based on knowledge exist, current approaches do not provide a holistic framework to perform systems architecting based on formalized knowledge while reducing development time and handling complexity as integral part of conceptual design. Hence, the holistic, model-based framework for knowledge-based systems architecting, including a template-based method for knowledge conservation and the selection of a suitable tool for modeling systems architectures, is presented.

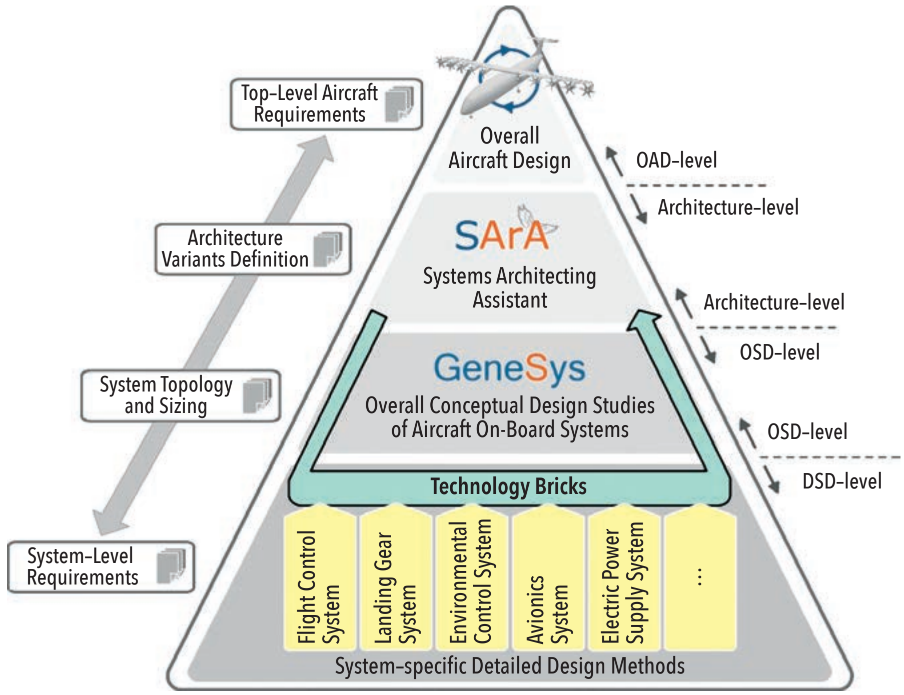


Figure 1. Levels of abstraction of the aircraft conceptual design phase from the perspective of systems engineers (Kuelper et al. 2022)

This paper consists of seven sections. Section 2 describes the overall systems design framework, whereas section 3 gives an introduction into knowledge-based engineering. The developed model-based framework is presented in section 4 including a requirements analysis and the presentation of the database concept. In section 5, the most suitable tool for modeling knowledge-based systems architectures is presented. Afterwards, the usability of the framework is demonstrated in section 6, followed by a conclusion and outlook in section 7.

OVERALL SYSTEMS DESIGN FRAMEWORK

In this section, the established overall systems design framework is presented which is the basis for the developed model-based framework for knowledge conservation and reuse for systems architecting. During aircraft conceptual design, the maturity of aircraft on-board systems is gradually improved by validation of requirements for systems, sub-systems, and components (Bielsky et al. 2021). To this end, time-dependent simulation models are developed to perform system behavior analyses. However, this is a time-consuming process. Thus, detailed analyses of OBS architectures are limited to a small number of variants. Such variants are identified by performing concept studies on higher abstraction levels. Four different levels for OBS design are introduced for the aircraft conceptual design phase (Bielsky et al. 2021, Juenemann et al. 2019). As shown in Figure 1, these four abstraction levels are structured in overall aircraft design (OAD), systems architecting, overall systems design (OSD), and detailed systems design (DSD) (Kuelper et al. 2022).

As part of the first abstraction level, OAD is performed. It includes the definition of geometric characteristics of the aircraft and top-level aircraft requirements (TLARs) (Kuelper et al. 2022). To already consider aircraft OBS at this level, low-fidelity methods such as regression functions and statistical methods are used to estimate, for example, the total mass of the on-board systems (Bielsky et al. 2021).

The second abstraction level consists of systems architecting which is performed by using the *systems architecting assistant (SArA)* methodology developed at the Institute of Aircraft Systems Engineering (FST) of Hamburg University of Technology (TUHH) (Kuelper et al. 2022). With this methodology, systems architecture variants for aircraft OBS are defined using a mainly knowledgebased approach to consider findings from existing systems architectures to open the design space for innovations. Since existing aircraft developments have shown that aircraft systems, sub-systems, and components are mainly driven by recurring design patterns, following a knowledge-based approach allows for the generation of many promising variants while reducing development time and costs

(Kuelper et al. 2022). Systems architectures, which are defined during this abstraction level, are described as *logical systems architectures*, meaning that a system is described based on its logical components and interdependencies including only a technology pre-selection. The other two defined architectural abstraction level are *functional* and *physical* (Hause et al. 2022, Kuelper et al. 2022). Furthermore, systems architecture variants are also evaluated using *SArA*. With the evaluation of architecture variants and a pre-selection of technology concepts, the design space for OBS architectures for a given aircraft design is significantly reduced to only relevant variants (Kuelper et al. 2022).

After the definition, evaluation, and selection of relevant systems architectures, the overall systems design software tool *GeneSys* is used as part of OSD in the third abstraction level to perform concept studies, evaluating the effect of the different architectures on aircraft level (Kuelper et al. 2022). *GeneSys* consists of different modules for generating the systems topology (components positioning and connections routing) and for system sizing (Bielsky et al. 2023). Based on the generated topology, parametric system sizing is performed, including the consideration of relevant interdependencies between the considered on-board systems (Juenemann et al. 2019). Rapid concept studies can be performed to further evaluate systems architectures and technologies, continuing to reduce the design space (Bielsky et al. 2021). Few relevant systems architecture variants remain. For these variants, time-dependent simulation models are developed as part of the DSD in the fourth abstraction level.

KNOWLEDGE-BASED ENGINEERING

This section gives an overview over knowledge-based engineering. In general, knowledge is an abstract, fuzzy concept. It consists of accessible and experience-based information and data (van der Laan 2008). To work with knowledge, an approach for handling and managing knowledge is necessary (Despres et al. 1999). Managing knowledge, that is, collecting, formalizing, storing, and providing knowledge, poses challenges in the context of engineering due to system complexity or intellectual properties (Mayrhofer et al. 2005). Furthermore, knowledge in engineering is typically available in various forms, such as databases, products, designs, processes, rules, literature, and human experts (Reddy et al. 2015). In the context of this paper, knowledge is defined as information, data, and experiences about existing OBS architectures and technologies but in an unstructured, non-standardized form. Formalized knowledge is defined as knowledge that has been organized and structured into a standardized format, which is conserved, investigable, and reusable.

To use formalized knowledge, the knowledge-based engineering (KBE) approach can be applied. Based on automating repetitive and routine tasks, this approach is typically associated with an increased development speed (Page Risueño et al. 2019). KBE enables a clarified, rationalized, and less-biased design space exploration (Verhagen et al. 2012). Furthermore, KBE is used to effectively collect, store, and provide formalized knowledge.

Advantages and challenges of KBE. Besides an increased development speed based on automating tasks, KBE is characterized by higher efficiencies, less iterations, and improved interdisciplinary collaboration (Page Risueño et al. 2019). Using KBE, an engineer has more time to focus on creative design tasks during conceptual design (van der Laan 2008). In addition, formalized knowledge and KBE are often an integrated part of MBSE approaches using central or distributed data storage (Zheng et al. 2021). However, since knowledge is often unstructured, formalizing knowledge is a time consuming process reasonable only for systems with significant uncertainty, complexity, and long development times (Verhagen et al. 2012), which all apply to the process of aircraft conceptual design. To ensure ongoing benefits of KBE, the formalized knowledge must be updated regularly creating additional workloads (Page Risueño et al. 2019). In total, KBE seems suitable for knowledge-based systems architecting.

Current model-based approaches based on knowledge. The framework of this paper considers existing model-based approaches using formalized knowledge as foundation. An ontology for managing formalized knowledge and performing design space exploration using an MBSE approach is described by Zheng et al. (2021). Fuchs et al. (2021) describe a method where knowledge, requirements, and system interrelation are used within models to automatically design aircraft cabin reducing development time. Furthermore, Fuchs et al. (2022) present a model-based approach for virtually reconfiguring aircraft cabin considering requirements, modeled system architectures, and a knowledge database. Pfennig (2012) presents a knowledge-based approach for designing aircraft high-lift system based on models including physical laws and geometrical information stored in a database, thus enabling the use of formalized knowledge already during conceptual design. Methods for capturing knowledge using machine learning are presented in Quintana-Amate et al. (2017). Sanya et al. (2014) provide an ontology-based, platform independent KBE framework to ensure conservation of formalized knowledge for many years by adapting existing model-based approaches. Judt et al. (2012) present an approach for model-based architecture enumeration and analysis based on a component database including experts' knowledge to provide formalized knowledge simultaneously to different architects. Yang et al. (2021) describe an approach for managing knowledge in the context of MBSE by transforming modeled architectures into graphs using a graph and property-based method for question answering. Younse et al. (2021) provides an MBSE approach for capturing architectural knowledge and managing system complexity, and states its benefits over a traditional, document-based systems engineering approach. Furthermore, three methodologies for KBE which can be used in a model-based approach are presented by Verhagen et al. (2012) and Reddy et al. (2015): MOKA, an informal model for problem definition, KOMPRESSA, similar to MOKA but with risk analysis and management, and KNOMAD, which highlights KBE as part of the design process focusing on the user.

MODEL-BASED FRAMEWORK FOR KNOWLEDGE CONSERVATION AND REUSE

To generate and evaluate systems architecture variants as part of *SArA*, formalized knowledge needs to be provided to the engineer. The developed framework based on KBE is used to collect, organize, and formalize existing and newly acquired knowledge about systems architectures. It enables effective and efficient knowledge-based systems architecting. To develop this framework, requirements are analyzed and a knowledge storing method is developed.

Requirements Analysis

The first step towards the development of a knowledge-based framework consists of identifying and defining requirements (Page Risueño et al. 2019). Based on literature research and individual needs relevant requirements are identified and are listed in detail in Table 2 in the Appendix.

First, to ensure a seamless process chain for on-board systems design, the knowledge-based framework shall be integrated in the conceptual design phase and holistically cover systems architecting and overall systems design. Therefore, knowledge needs to be formalized, conserved, and reused. Knowledge is formalized by modeling an existing systems architecture and then exporting it to the standardized storing method of this framework. Different methods for storing knowledge about

Table 1. Criteria for an MBSE tool for systems architecting with weighting parameters

Modeling language	Tool capabilities	Interaction and usability
• Abstraction capability (3) • Complexity handling (3) • Variants handling (1) • Traceability (3) • Modeling standardization (2)	• Graphical interface (2) • Model scalability (1) • Model reusability (2) • Model modifiability (2) • Concurrent modeling (1) • Analysis capability (3) • Constraint checker (1) • Automation capabilities (1) • Future prospect (1)	• User guidance (2) • Multidisciplinary modeling (2) • Interaction with *iDAM* (3) • Interaction with *GeneSys* (3)

systems architectures are considered. This includes text-based methods, for example, using *Word* files or machine-readable eXtensible Markup Language (XML)-files. Alternatively, graphical representation methods, such as storing architecture images within *PowerPoint* files, and a model-based method storing architectures as independent files in the format of the modeling tool are considered. Table based approaches storing systems architectures, for example, as *Excel* sheets or within a database, are also assessed. Since in the long term, formalized knowledge about many systems architectures needs to stored, big data must be manageable. Furthermore, the stored formalized knowledge shall be queryable and reusable in a standardized manner while also considering different user access rights. Based on these needs, a database is selected as most suitable method for storing, linking, querying, and reusing formalized knowledge.

The database needs to closely interact with an MBSE tool for *SArA*, as shown in Figure 2, to conserve and provide formalized knowledge for systems architecting. The tool for systems architecting needs to exchange information about selected systems architectures with *GeneSys* for OSD (cf. section 2). Moreover, acquired knowledge during OSD needs to be fed back to the database. Additionally, the framework needs to be generic, flexible, modifiable, and reusable even for disruptive concepts (Page Risueño et al. 2019). The usability of the framework is further increased by implementing a user interface allowing for traceability of results or entries (Sanya et al. 2014).

Second, to provide accessible and investigable formalized knowledge to the engineer, the *intelligent Data Analytics and Management (iDAM)* database method has been developed at FST. A database method is required to be accessible from different locations and engineers simultaneously to increase usability (Judt et al. 2012). To increase the gain of implementing a database, it needs to be generic enough to be reusable for future aircraft and systems architecture concepts. Furthermore, data and information stored within the database needs to be modifiable and updateable to ensure that newly acquired knowledge can be added (Page Risueño et al. 2019), such as information and experiences about hydrogen supply system architectures. Preferably, updating data shall be performed regularly so that stored formalized knowledge is not outdated.

Third, requirements for a model-based systems architecting tool as part of the developed framework are identified based on academia and industry needs as described by Watkins et al. (2020), Bonnet et al. (2016), Sanya et al. (2014), and Page Risueño et al. (2019). Based on these requirements 18 criteria for an MBSE tool are defined and categorized into three groups: "modeling language" that is used by the tool, "tool capabilities", and "interaction capabilities and usability" of the tool. As shown in Table 1, the criteria are prioritized based on importance with the weighting factors three, two, and one (number in brackets) similar to a categorization into "must-have," "should-have," and "couldhave" requirements, respectively. Thus, the importance of a requirement for the MBSE tool is represented in the criteria (Franceschini et al. 1999). The weighting factor was defined based on engineers experience and personal needs within a workshop. Therefore, a decision bias cannot be completely ruled out.

The ability to handle different levels of model detail and complex systems with many components and interactions are two key capabilities of the modeling language. Further, defined modeling standards support multi-domain applicability as well as reduction in development time. The criterion for traceability is indispensable due to safety-criticality of many aircraft OBS, that is, the engineer needs to clearly identify from which requirement and func-

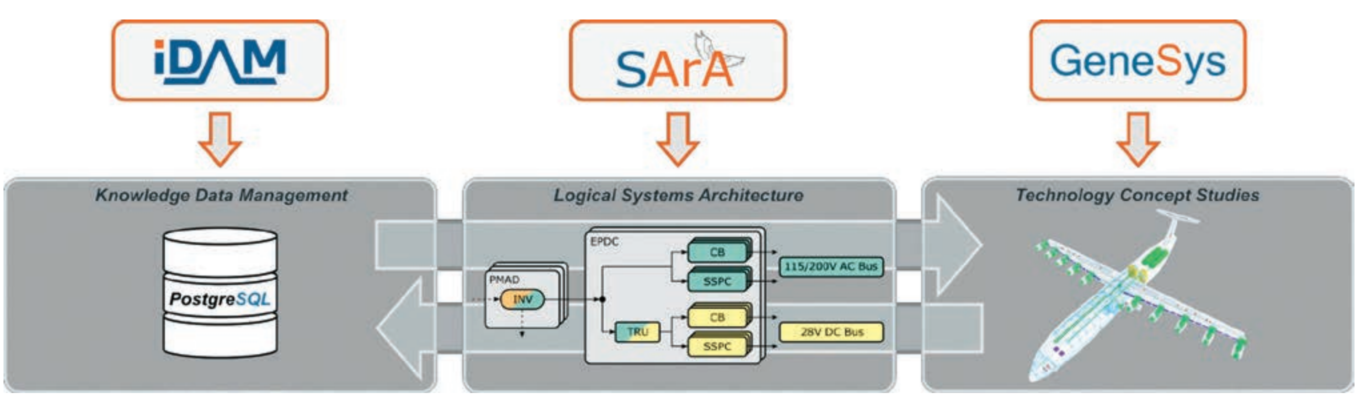


Figure 2. Holistic knowledge-based framework as part of the aircraft conceptual design phase

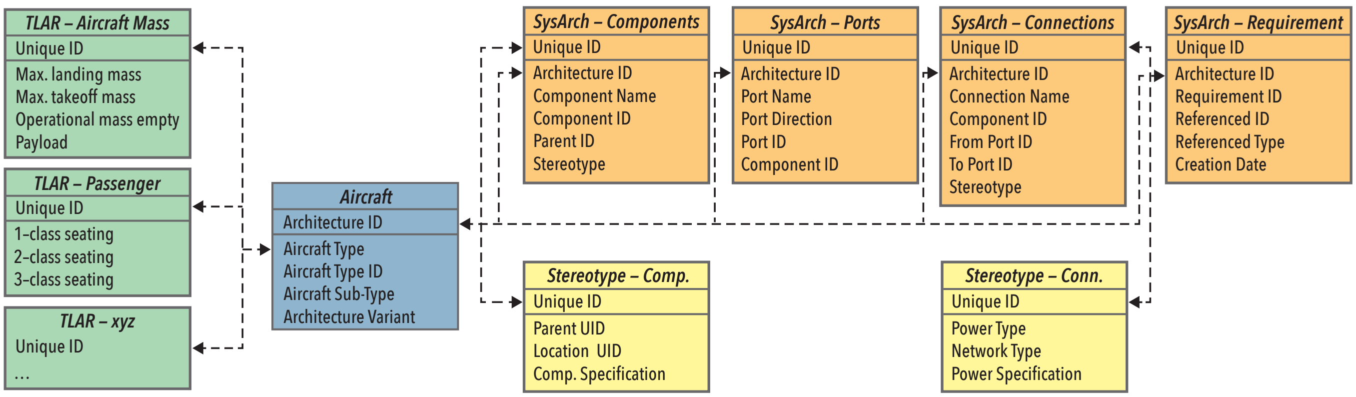


Figure 3. Database schema for conserving and reusing formalized knowledge about systems architectures

tion a logical component and architecture is derived.

To ensure the seamless process chain during OSD, interaction capabilities with *iDAM* and *GeneSys* are essential. Furthermore, criteria like user guidance and multidisciplinary modeling need to be investigated to assist the engineer and to increase development speed. Tool capabilities include mainly "should-have" and "could-have" requirements which assist the systems architecting process but are non-essential, such as concurrent modeling or automation possibilities. Further, to increase usability of systems architecture models, they are required to be investigable including analysis capabilities. Moreover, model reusability, modifiability, a clear graphical representation, and an interface should be implemented in the tool.

Integrated Database Concept

A suitable and in this paper selected database concept for *iDAM* is the open source, object-oriented *PostgreSQL* database system (PostgreSQL Global Development Group 2023). To store and reuse formalized knowledge about systems architectures, a generic database schema is developed. A schema describes the structure, patterns, meanings, and interrelations of formalized knowledge within the database (Uschold 2015). In this paper, a schema and not an ontology is developed due to the requirement that stored knowledge within *iDAM* must be analyzable and investigable using the database language *SQL* for data querying. The developed database schema is presented in Figure 3.

The database schema of this relational database consists of several tables, each consisting of a column of unique identifiers ("Unique ID"). Four different types of information are stored in the tables, which are categorized by the four different colors: top-level aircraft requirements ("TLAR"), aircraft information ("Aircraft"), systems architectural information ("SysArch"), and properties ("Stereotype"). "Aircraft" consists of a list of information about aircraft type, type ID, sub-type name, and the corresponding systems architecture variant. "SysArch" consists of architectural data about components, requirements, interfaces, and connections. "Stereotype" tables contain information about component and connection properties, such as power specifications.

Rows from one table can be connected to rows of other tables (1-n connection) by linking unique entries, as shown in Figure 2. In doing so, TLARs are linked to aircraft and architectural information. Thus, the requirement for accessibility and investigability of stored formalized knowledge is satisfied, since existing architectures can be accessed and modified. Data is updated based on created systems architecture models within the MBSE tool. Thereby, formalized knowledge about systems architectures of current and past aircraft is conserved. Moreover, formalized knowledge within *iDAM* can be passed to the MBSE tool for systems architecting in an automated way, enabling the recreation of full or partial systems architectures.

ANALYSIS OF RELEVANT MBSE TOOLS

Based on the criteria for the MBSE tool for knowledge-based systems architecting, relevant modeling languages are introduced and different tools for modeling systems architectures are evaluated. The tool that scores most points in the criteria, thus fulfilling the requirements at best, is selected.

Common Modeling Languages and Tools for Systems Architecting

As mentioned before, a suitable MBSE tool for systems architecting is needed to enable the holistic, model-based framework (cf. Figure 2). First, typical modeling languages for systems architecting are considered since being one of the three tool criteria categories (cf. Table 1). A standardized language enables consistency and repeatability of the modeling process. Commonly used languages for systems architecting are, among others, Unified Modeling Language (UML), Systems Modeling Language (SysML), Eclipse Modeling Framework (EMF), and Architecture Analysis and Design Language (AADL). UML is a general-purpose modeling language designed to assist software engineers during development by modeling systems structure and behavior (Holt, 2004). SysML as a semiformal, graphical language is used during specification, design, and verification of complex systems (Weilkiens 2008). With SysML, systems architectures can be modeled on different levels of abstraction, such as functional, logical, and physical, however, a defined method is not included in SysML (Hause et al. 2022, Schäfer et al. 2023). EMF is a framework facilitating code generation. It includes XML, Java, and UML. Models can be created in either one and then transformed into the other languages (Steinberg et al. 2009). AADL is used for a standardized representation during embedded systems architecture generation and validation (Kordon 2013). However, due to the focus on embedded systems for a detailed description of software and hardware, modeling other aircraft OBS is not ideal.

Second, various tools based on mentioned modeling languages exist. One tool is *Capella*, which is implemented mainly based on SysML. It is specifically developed for systems architecting and includes the modeling methodology ARCADIA (Nowodzienski et al. 2022, Voirin 2018). Based on ARCADIA, *Capella* provides user with modeling guidance. However, modeling automation and representing systems of systems are not directly included in ARCADIA (Nowodzienski et al. 2022). Another SysML based modeling tool is *Cameo Systems Modeler*. It is developed for system engineers to facilitate the creation of executable SysML models (Casse 2017).

It is not purposely developed for systems architecting. Other SysML based tools like IBM Rational Rhapsody are not further analyzed after initial consideration. They include superfluous functionalities not needed for systems architecting. In this paper, the focus is on selecting an MBSE tool for knowledge-based systems architecting as integral part of the model-based framework.

As an example for an EMF-based modeling tool the *Avionics Architect* is analyzed in detail. It is specialized on the description of integrated modular avionics (IMA) platforms using a formalized meta model. It provides design guidance methods, analyzation and evaluation methods, a MATLAB interface, and an optimization toolbox (Annighoefer 2019). However, the *Avionics Architect* is not limited to avionics and can be used for other mechatronic systems. In an UML-based manner, an object-oriented approach is used to define element classes, which are used as element bricks for architecture generation. However, since the *Avionics Architect* is a physical and detailed systems architecture design tool, a lot of knowledge about the systems is required which is typically not available in the aircraft conceptual design phase.

Moreover, modeling tools exist which are based on individual modeling languages, such as *MathWorks System Composer* as part of the MATLAB environment. Being based on Simulink, it includes an UML-like modeling language with state-machine diagrams and allocation matrices (The MathWorks 2022). *System Composer* is a tool for modeling systems and software architectures as part of MBSE on functional, logical, and physical level. An interface to MATLAB is included enabling behavior simulations and requirements mapping. System and component properties are added using meta data (The MathWorks 2022). Furthermore, architectures can be imported and exported. In contrast to *Capella, System Composer* does not provide a modeling methodology, so that the development of individual methods is both supported and necessary. Even though, it was released in 2019, it is already used in industry, for example, by Gulfstream (Watkins et al. 2022).

Existing Flight Control System Architecture for Tool Evaluation

Modeling capabilities of the four modeling tools are investigated based on the flight control system (FCS) architecture of an *Airbus A320*. In this paper, this architecture is selected since being well known and understood. The focus lies purely on evaluating the four different tools for modelbased systems architecting.

The FCS of an *A320* consists of a primary and a secondary FCS architecture. The primary FCS architecture consists of four aileron, four elevator, three rudder, and ten spoiler actuators. Due to the safety criticality of FCS, these actuators are supplied by three independent hydraulic power supply systems, which are described within the architecture of an *Airbus A320* as blue, green, and yellow (cf. Figure 4). The secondary FCS consists of slats and flaps actuated by central drive systems. The drive systems of the *A320* FCS architecture are powered by central power control units (PCUs), which are redundantly supplied by hydraulic power. Further components, such as brakes, are not shown here. In general, the FCS architecture displays the complexity of safety critical aircraft onboard systems.

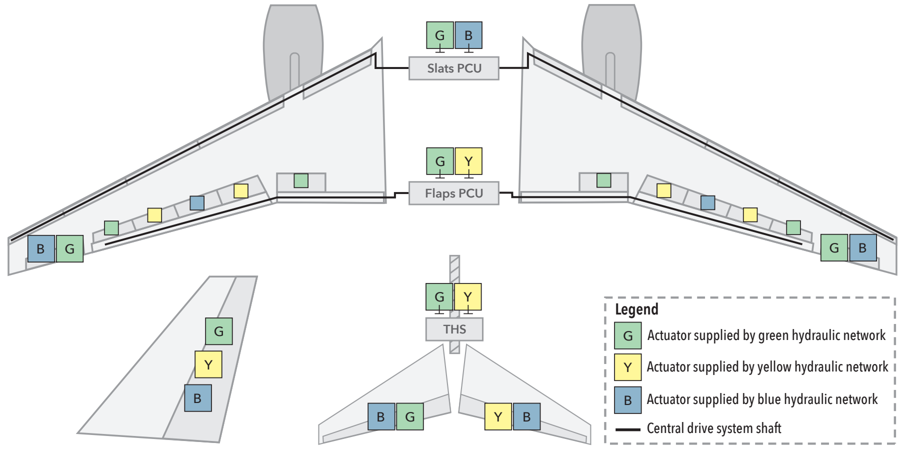


Figure 4. Schematic flight control system of an Airbus A320 and hydraulic power supply [based on (Moir et al. 2011), adapted by authors]

Evaluation and Selection of MBSE Tool

The FCS architecture is modeled in *Capella, Cameo Systems Modeler, System Composer*, and *Avionics Architect*. Afterwards, the created models are evaluated based on the defined and weighted criteria (cf. Table 1). The fulfillment of the criteria is rated based on a linear scale from zero to five points as part of the quality function deployment (QFD) method (Franceschini et al. 1999). Zero points represent a not implemented criterion; one point demonstrates a poor fulfillment. Higher points embody higher fulfillment of the criteria with a maximum of five points demonstrating a fully satisfied criterion.

$$S = \sum_{i=1}^{n} w_i \cdot r_i \qquad (1)$$

Per evaluated tool, the total score S is determined using equation 1. The total score is based on the sum of weighting factor wi and the rated points ri per criterion (index i). The most suitable MBSE tool for the framework is selected based on the highest score. It was deliberately decided to use QFD with weighting due to the different importance of requirements. However, a bias cannot be completely ruled out using this approach. The results per tool are shown graphically in Figure 9 and in detail in Table 3 in the Appendix.

Evaluation of *Capella*. In *Capella*, functions, logical and physical system components are modeled as blocks, which can be placed inside each other to demonstrate a hierarchical relationship (cf. Figure 5). A standardized modeling language is included based on SysML. Handling solution variants is not yet considered. In *Capella*, different block types are used to model systems architectures: component blocks (black or white background) are used to model container elements, while actors blocks (blue) model system elements with a behavior. Both uni- and bidirectional connections can be modeled and highlighted. Connections are modeled as direct links by default, significantly reducing model clarity and thus, increasing additional, manual workload for a clear representation as shown in Figure 5.

Based on ARCADIA, the criteria abstraction capabilities and user guidance for modeling systems architectures on different levels are fully satisfied. Previously identified functions can be mapped to logical components which themselves can be allocated to physical components using allocation matrix. This satisfies the requirement for traceability and enables handling of systems complexity. Script based modeling is not directly supported in *Capella* requiring a Python add-in, therefore reducing automation capabilities. Model scalability did not pose a challenge. In general, information about architecture and components can be added using properties. However, it is not trivial to add additional information like

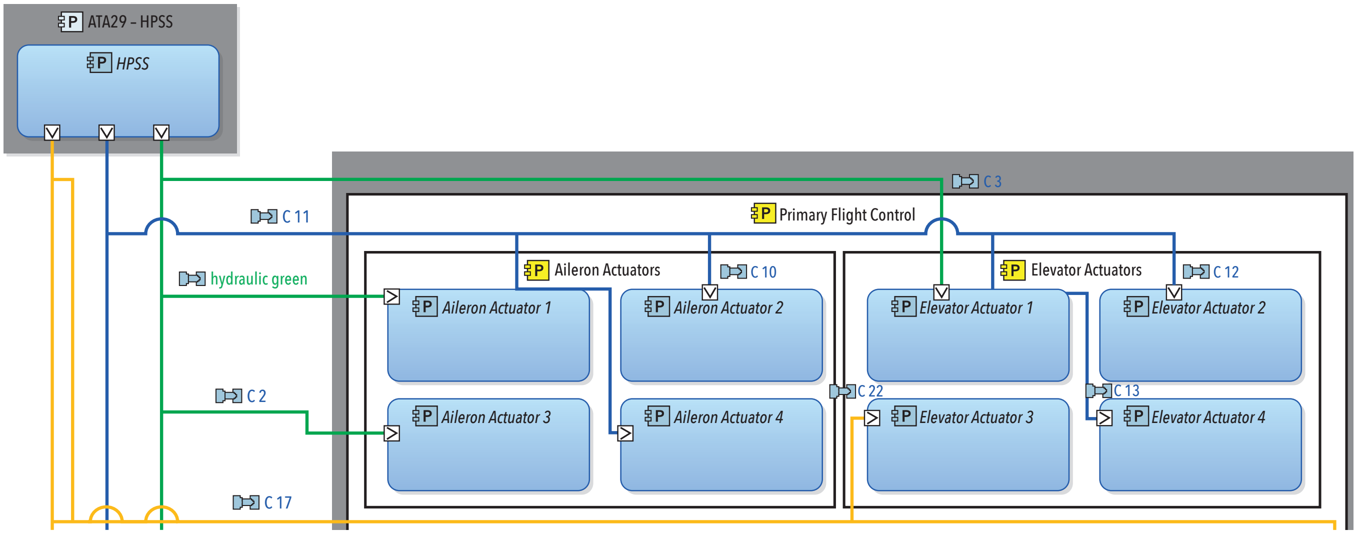


Figure 5. Excerpt of A320 FCS including hydraulic power supply modeled in Capella

power specifications, such as "3000 psi," which is required for preliminary systems design with *GeneSys*. Exporting systems architectures in a standardized format to *GeneSys* poses challenging and requires add-ins. Moreover, to perform behavior simulations an interface to, for example, Simulink is needed (Nowodzienski et al. 2022). This decreases suitability of *Capella* for the framework. Overall, *Capella* scores 123 points (cf. Figure 9).

Evaluation of *Cameo Systems Modeler*. Similar to *Capella*, in *Cameo Systems Modeler* blocks and parts are used to model functions, logical and physical system components. A hierarchical relationship is displayed by placing blocks or parts inside each other (cf. Figure 6). *Cameo Systems Modeler* is developed based on the standardized modeling language SysML. Among others, block and internal block diagrams are used to demonstrate the structure of an architecture. Behavior is demonstrated based on, among others, state machine and activity diagrams. Nonetheless, to perform detailed calculations and behavior simulations, an interface to other tools, such as Matlab, Simulink, or Maple, is required (Casse. 2017). Additionally, exporting systems architectures in a standardized format to *GeneSys* poses a challenge and requires mentioned interfaces. These aspects decrease suitability of *Cameo Systems Modeler* for this framework. Interaction with *iDAM* is possible based on plugins.

In *Cameo Systems Modeler*, handling component or technology variants is not yet implemented and requires additional software, for example, the variant management tool *pure::variants* (pure-systems GmbH 2023). Variants handling shall be facilitated with a future SysML release. Uni- and bidirectional connections can be modeled. The created aircraft OBS architecture layout can be updated automatically to increase the graphical representation. This is a good foundation, nevertheless, manual workload is still necessary to improve model clarity, especially for extensive and complex architectures. The criteria abstraction capabilities, complexity handling, and traceability are fully satisfied. Systems architectures can be modeled on different levels of abstraction while allowing for a mapping between diagrams to ensure traceability. A user guidance or method for modeling systems architectures method is not provided requiring individual methods. Script based modeling is not directly supported in *Cameo Systems Modeler*, reducing automation capabilities. Information about components and connections can be added using customized stereotypes to add additional information like power specifications, such as "3000 psi". Overall, *Cameo System Modeler* scores 127 points (cf. Figure 9).

Evaluation of *MathWorks System Composer*. Modeling systems architectures in *System Composer* consists of three elements: blocks, which represent functions or components, ports, which enable in- and outputs, and connections, which ensure uni-directional data or power exchange. Blocks can define functional, logical, or physical components of a system enabling abstraction capability. Different abstraction levels are distinguished based on component properties using stereotypes. Attributes and meta data, for example, power specifications of the hydraulic network, such as "3000 psi", are represented in stereotypes. Since *System Composer* is part of MATLAB environment, architectural information can be imported and exported to

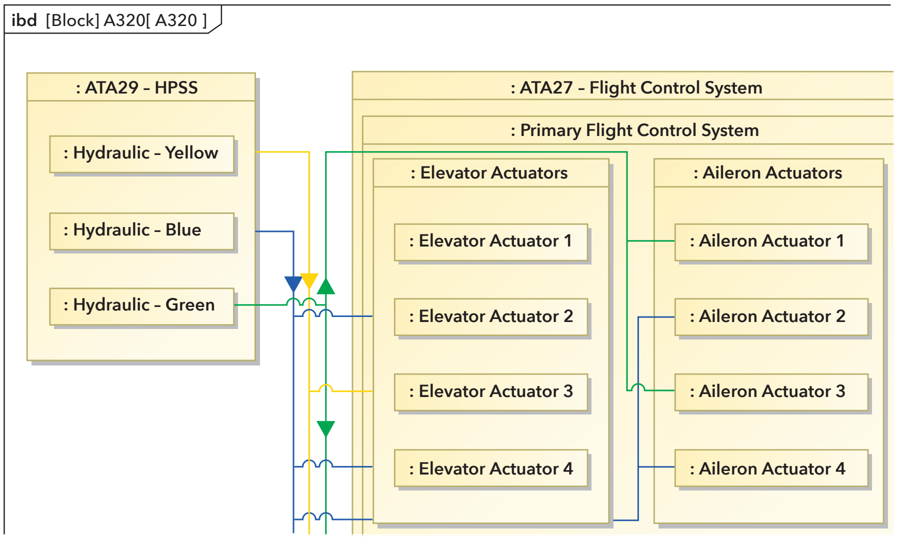


Figure 6. Excerpt of A320 FCS with hydraulic power modeled in Cameo Systems Modeler

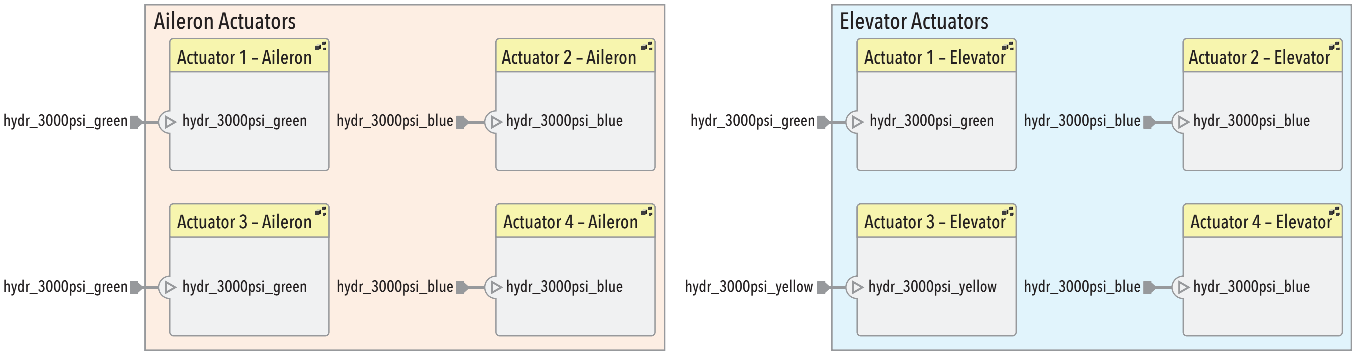


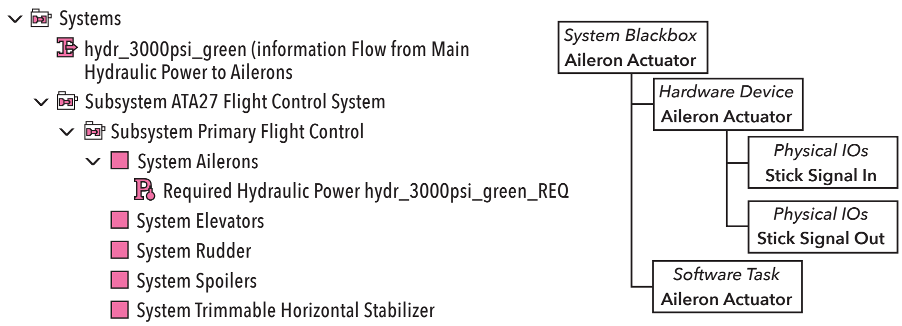
Figure 7. Excerpt of A320 FCS including hydraulic power supply modeled in System Composer

iDAM using a MATLAB toolbox. Furthermore, a direct interface to *GeneSys*, which is implemented in MATLAB, is possible.

In Figure 7, the lowest hierarchy level is shown with the logical system components. To get a better understanding of the entire architecture and to handle complexity, detail architecture views can be created, components can be categorized and grouped using colored areas to increase visualization. Allocation matrices (requirements to functions, functions to logical components, etc.) are included for traceability. In addition, systems architectures can be analyzed and evaluated using MATLAB scripts. As mentioned previously, a standardized modeling method is not officially provided requiring individual methods not satisfying the requirement for a standardized language. However, individual methods have already been developed and published, such as the *eSAM* method by Watkins et al. (2022). Systems architectures can be created using scripts. Moreover, models can easily be modified and adjusted with the possibility to model product variants. Overall, *System Composer* scores 136 points (cf. Figure 9).

Evaluation of the EMF-based *Avionics Architect*. Due to the nature of EMF, the user interface of the *Avionics Architect* is a tree-based, hierarchical architecture representation ensuring abstraction capabilities, as shown in Figure 8 (a). However, a graphical visualization of the components and their connections is not implemented, reducing the readability and understandability of the model.

Architecture properties are added to the model based on data models similar to stereotypes in *System Composer*. Additionally, other elements can be referenced as property values. Figure 8 (b) shows a block diagram description of the element classes needed to describe an exemplary component ("Aileron Actuator") in a physical system architecture. It is important to note, that the *Avionics Architect* has a focus on avionics systems. Therefore, it is not ideal for other aircraft OBS.



(a) Tree-based systems representation (b) Component depiction

Figure 8. Excerpt of A320 FCS including hydraulic power supply modeled in the Avionics Architect

Due to the fact, that the *Avionics Architect* has an underlying meta model, it has a standardized modeling language for system architecting. Moreover, *Avionics Architect* is able to import and export architectural information, optimize, analyze, and automatically generate architectures. However, some features are not performed in the *Avionics Architect* but in MATLAB resulting in a continuous dependency. The interface to MATLAB enables interaction with *iDAM* and *GeneSys*. Reusability and modifiability of architectural elements are enabled based on flexible property definition and element classes. Furthermore, *Avionics Architect* has already been used in industry and research projects, as for design space exploration of the avionics platform of an *Airbus A350* (Annighoefer 2019). Since being an in-house tool of FST, change request are directly considered, but also create substantial implementation workloads. Requirements are linked to system elements via *strings* ensuring fundamental traceability capabilities. The criterion for model scalability is fully satisfied supporting also large models. In addition, variants are handled using container, however, without a clear graphical representation of the component variants. In general, the *Avionics Architect* is well suited for Detailed System Design, however this is not need or required for system architecting. Overall, the *Avionics Architect* scores 115 points, as shown in Figure 9.

Results of evaluation and tool selection. Based on the presented and experienced advantages and disadvantages of the four considered tools *Capella, System Composer*, and *Avionics Architect*, the scoring results are depicted in Figure 9 and also in detail in Table 3 in the Appendix. To get a clear understanding of the scoring results, the sequence of requirements of Table 1 is maintained, that is, the lowest sub-block in Figure 9 (a) represents the first modeling language capability: "abstraction capability". It can be seen that *Capella* scores most points in category "modeling language," whereas

System Composer scores most points in "tool capabilities", and "interaction and usability". Overall, *System Composer* scores most points by fully satisfying many criterion and thus requirements. One reason is that most points are scored in the category of "must-have" requirements, such as "abstraction capability" or "database interaction capability" (cf. Table 1), which are weighted triple. As shown in Figure 9 (b), *Capella* scores most points in the category of "should-have" requirements. Overall, *System Composer* is identified as the most suitable MBSE tool for modeling aircraft OBS architectures for the presented holistic, knowledge-based framework.

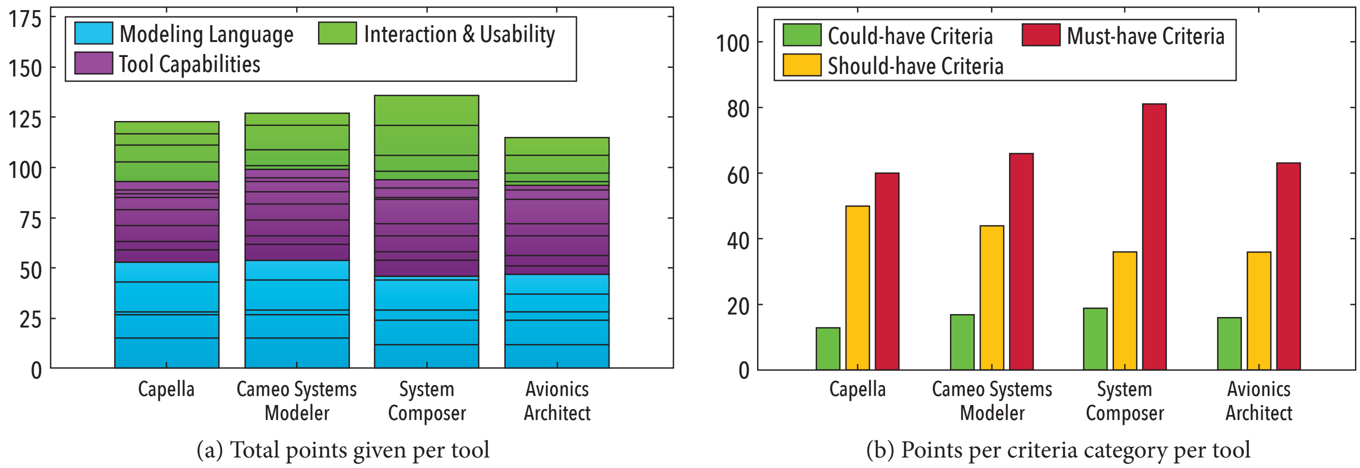


Figure 9. Scoring results of evaluated MBSE tools for knowledge-based systems architecting

APPLICATION OF THE KBE FRAMEWORK TO A HYDROGEN CONCEPT AIRCRAFT

The developed framework for knowledge-based systems architecting for the aircraft conceptual design phase is applied in the scope of first storing formalized knowledge about existing systems architectures. Secondly, formalized knowledge within *iDAM* is accessed, investigated, and used for systems architecture generation of a novel and disruptive concept aircraft.

Conservation of Formalized Knowledge

To conserve knowledge about systems architectures within *iDAM*, knowledge is formalized by first creating and modeling systems architectures in *System Composer*. Besides the FCS architecture of an *Airbus A320*, knowledge about the entire architecture is collected based on a literature research and consulting experts. In addition, knowledge about other aircraft, such as the *Airbus A330*, *Airbus A350*, and *ATR 72*, is identified and collected. Thereupon, systems architectures are modeled in *System Composer* as part of *SArA*, following a standardized modeling method developed at FST. As shown in Figure 10, on the highest hierarchical model level a systems-based representation based on ATA-chapter is used, grouping the systems into three categories: power generation, distribution, and consumption. Lower model hierarchy level represent higher details, such as components, as already shown in Figure 7. To comply with conceptual design, only relevant systems with high complexity, significant mass shares, or substantial power demands are considered and abstracted to logical architecture level. However, this creates modeling limitations since some systems include interfaces, for example, of the electric power supply system (EPSS), which are unused due to neglecting lower model fidelity for some systems during conceptual design. In general, manually modeling systems architectures is a time consuming process but enables investigable and usable formalized knowledge.

Second, due to the ability of *System Composer* to directly interact with a database, the modeled architecture is exported to the database schema of *iDAM*. This interaction between *iDAM* and *SArA* is fully automated based on MATLAB scripts.

Hydrogen-powered Concept Aircraft

The hydrogen-powered regional concept aircraft *ESBEF-CP1* with a seating capacity of 70 passengers based on an *ATR 72*-like aircraft is proposed, as shown in Figure 11 (Kuelper et al., 2022). *ESBEF* is the German acronym for "Development of Systems and Components for Electrified Flight" and *CP1* stands for "Concept Plane 1."

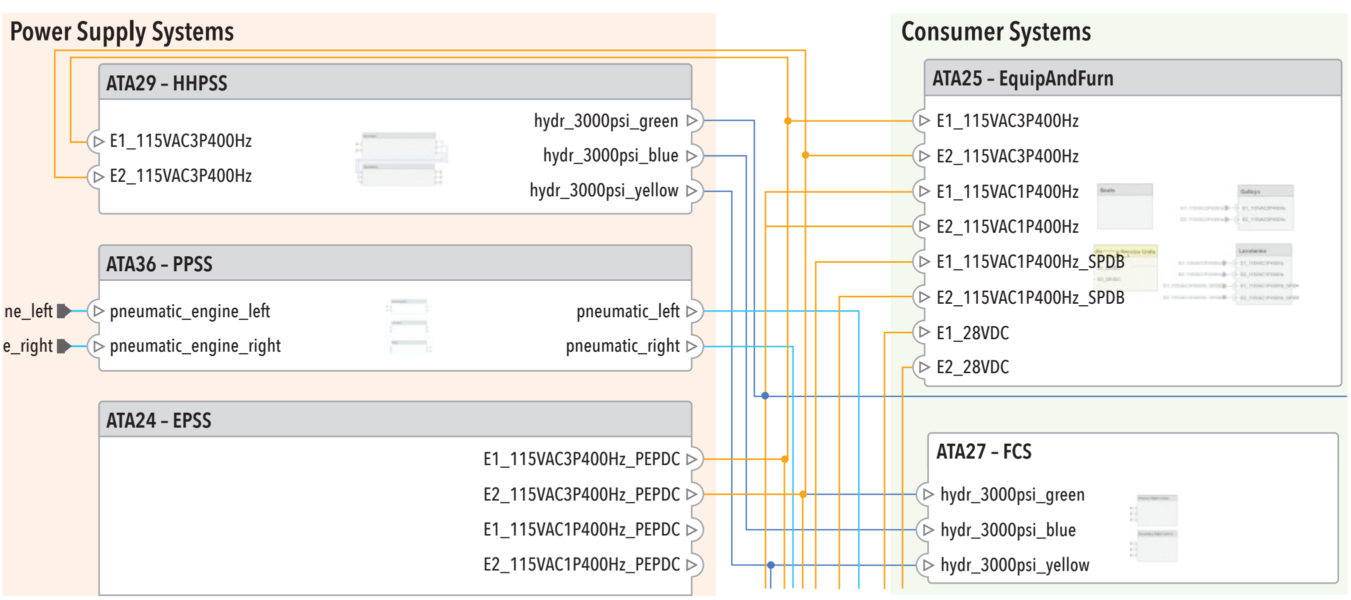


Figure 10. Top-level view of partial Airbus A320 systems architecture model in System Composer

Figure 11. Hydrogen-powered concept aircraft – ESBEF-CP1 (Kuelper et al. 2022)

This disruptive concept aircraft contains of ten propulsion units (pods) including fuel cells, thermal management, air supply, and electric power management units. Two cryogenic tanks are installed in the aft fuselage to use liquid hydrogen (LH2) as energy source. The on-board systems architecture is grounded on a *more-electric-aircraft* approach including, for example, an electrified environmental control system and an electrified hydraulic power supply system architecture (HPSS) (Kuelper et al. 2022). The HPSS is not powered by engine driven hydraulic pumps, as done conventionally, but by redundantly supplied electric motor pumps as part of a central hydraulic power package (Bielsky et al. 2023).

Reuse of Conserved Knowledge for Systems Architecting

The systems architecture of *ESBEF-CP1* is manually developed, modeled, and exported to *iDAM* to preserve the gained knowledge in an organized and formalized manner. It is the authors opinion that this initial modeling step, especially for novel aircraft concepts, should remain a manual step to enable the creative process of systems architecting. However, to ensure satisfaction of safety requirements already during conceptual design and to assist the engineer during modeling, existing formalized knowledge about FCS within *iDAM* is used as foundation for generating the FCS architecture of *ESBEF-CP1*. The formalized knowledge is investigated using a *SQL* query, selecting existing FCS. Due to fulfilling safety requirements and being a well-known and understood architecture, *Airbus A320* FCS architecture is exemplarily selected for *ESBEF-CP1* to demonstrate the framework. MATLAB scripts enable an automated combination and generation of the modeled *ESBEF-CP1* systems architectures with the FCS architecture of *A320*, as shown in Figure 12.

By automatically generating systems architectures, full systems architectures can be recreated, or different architectures can be combined in an automated matter, as in this case. This automates repetitive tasks as described by KBE and assists the engineer during systems architecting. As shown in Figure 12, connections between the *Airbus A320* FCS block and the rest of the systems architecture still need to be connected manually. In the future, this can be automated to further assist the engineer by developing generic MATLAB scripts to automatically connect ports with the same assigned stereotype. Alternatively, a machine learning algorithm could be used to connect the blocks based on knowledge provided to the algorithm based on training data.

However, the existing *Airbus A320* FCS architecture is not fully adequate for the created *ESBEF-CP1* systems architecture. The *ESBEF-CP1* includes, for example, only flaps and no slats, only four spoiler surfaces, and only one hydraulic network, unlike *Airbus A320* FCS architecture (cf. Figure 4). Hence, in this case the *A320* FCS works as foundation for creating novel systems architectures and needs to be manually adapted within *System Composer* to comply with the *ESBEF-CP1* systems architecture. Alternatively, in the future various stored FCS architectures in *iDAM* can be combined and adapted using e.g., a machine learning (ML) algorithm to comply with the *ESBEF-CP1* systems architecture before automatically generating the entire systems architecture. However, it must be noted that sufficient training data and thus formalized knowledge is required to ensure feasible results from the ML algorithm.

It is noticeable that by storing architectures in *iDAM*, graphical block positioning and graphical representations, such as areas, are lost. This reduces the advantage of a clear graphical representation of model-based systems architecting. To increase usability of this framework again, further work is necessary to include also graphical information within *iDAM*. A concept for doing so is to store graphical information in a meta-data file or to develop generic templates to increase a clear graphical representation. Based on the automated created systems architecture in *System Composer* and the generic interface file between *SArA* and *GeneSys* (Kuelper et al. 2022), preliminary systems design on OSD-level is performed without further manual model adaptions.

CONCLUSION AND FUTURE WORK

A holistic, model-based framework for knowledge conservation and reuse for systems architecting is developed in this paper. It is based on a database concept, the *Systems Architecting Assistant* (*SArA*) methodology, and *GeneSys*. The identification of requirements, the development of a database concept to conserve and reuse

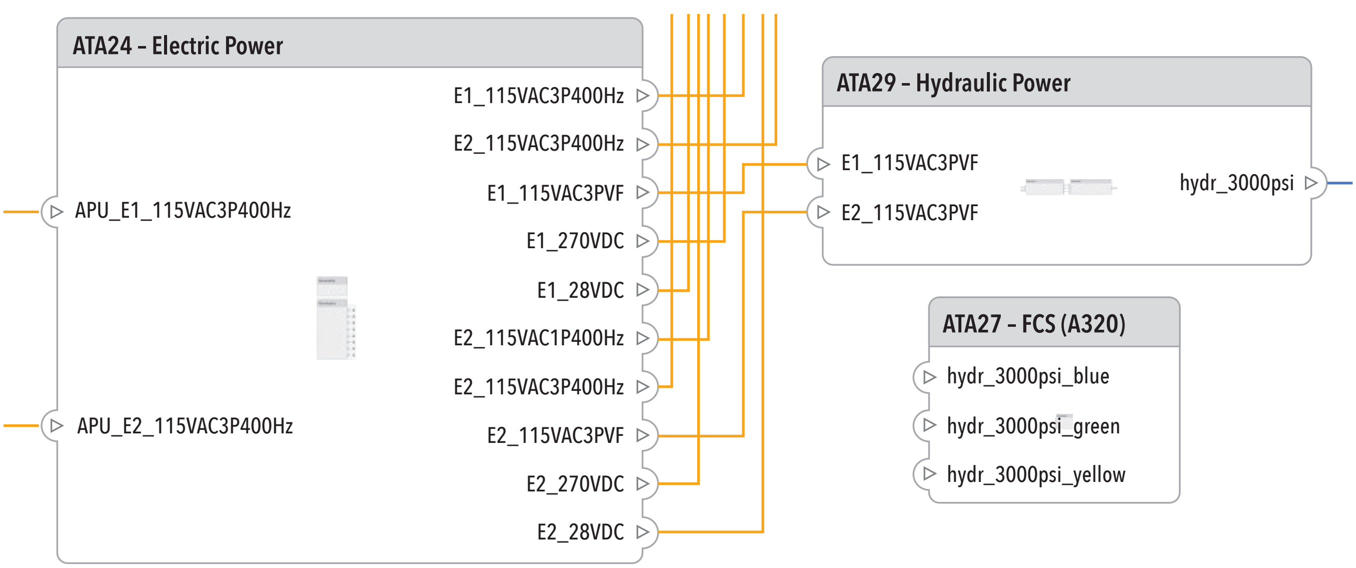


Figure 12. Partial model of the automatically generated ESBEF-CP1 systems architecture with FCS architecture from Airbus A320

formalized knowledge, and the selection of an MBSE tool for systems architecting are presented. Due to the importance of an MBSE tool as a key element for conserving and reusing formalized knowledge for systems architecting within the framework, evaluation of typically used modeling languages and MBSE tools is performed. *Capella* as SysML tool, *Avionics Architect* as EMF-based tool, and *System Composer* with an individual modeling language are assessed resulting in the selection of *MathWorks System Composer* as most suitable tool. The application of this framework is then demonstrated for a hydrogen-powered concept aircraft.

In general, the developed framework enables a rapid and partly automated approach for knowledgebased systems architecting as part of KBE. Existing and newly gained knowledge is identified, organized, formalized, and preserved in a database. Thus, formalized knowledge is available and useable to assist during mainly knowledge-based systems architecting as part of the aircraft conceptual design phase. Thereby, the overall development is accelerated and the engineer can focus on creative design tasks. This results in the ability to generate and evaluate a higher number of systems architecture variants. However, a modeling methodology in *System Composer* does not exist and graphical representations are lost due to storing systems architecture in the database. Furthermore, some manual tasks remain, such as adapting architecture bricks to fit into a created systems architecture, resulting in the necessity of further research in this field to increase assistance and automation, for example, by implementing a machine learning algorithm. Moreover, the developed framework focusses currently on formalized knowledge about systems architectures. The framework needs to be extended to also enable conservation and reuse of formalized knowledge for system components on logical level. This includes functions and technology bricks to create a technology library. ■

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Appendix

Table 2. Requirements for the knowledge-based framework

ID	Name	Description
R1	Seamless process chain	To ensure a seamless process chain for OBS design, the knowledge-based framework shall be integrated in the conceptual design phase
R1.1	Framework capabilities	The framework shall enable a generic and flexible structure for conceptual design.
R1.2	Integrate OSD process steps	The seamless process chain shall cover systems architecting and OSD.
R2	Knowledge storage	Existing and newly acquired knowledge shall be for stored.
R2.1	Knowledge formalization	Knowledge shall be stored in a formalized matter.
R2.2	Knowledge modifiability	Stored knowledge shall be modifiable.
R2.3	Knowledge reusability	Stored knowledge shall be reusable.
R3	MBSE tool for *SArA*	Systems architecting with *SArA* shall be performed based on an MBSE tool.
R3.1	Interface capabilities	The MBSE tool shall be able to exchange information with *GeneSys* and the knowledge storage concept via interfaces.
R4.2	Flexibility capabilities	The MBSE tool shall be generic enough so that models in this tool are flexible, modifiable, and resuable.
R4.3	Traceability capabilities	The MBSE tool shall enable traceability of require- ments and functions.
R4.4	Modeling language	The MBSE tool shall include a powerful and standardized modeling language to enable complexity, abstrac- tion, and variants handling.
R4.5	Tool capabilities	The MBSE tool shall include adequate tool capabilities such as a GUI, analysis, automation, and concurrent modeling capabilities and a constraint checker.
R4.6	Future prospect	The tool shall be supported also in the future.
R4.7	User guidance	The MBSE tool shall assist the user via guidance.
R4.8	Multidisciplinary modeling	The MBSE tool shall enable modeling for users of different disciplines and backgrounds.

Table 3. Detailed scoring of the four selected MBSE tools for systems architecting

Criteria (weighting factor)	Capella	Cameo Systtem Modeler	System Composer	Avionics Architect
• Abstraction capability (3)	5	5	4	4
• Complexity handling (3)	4	4	4	4
• Variants handling (1)	1	2	5	4
• Traceability (3)	5	5	5	3
• Modeling standardization (2)	5	5	1	5
• Graphical interface (2)	3	4	4	2
• Model scalability (1)	4	4	4	5
• Model reusability (2)	4	4	4	5
• Model modifiability (2)	4	4	3	3
• Concurrent modeling (1)	0	0	0	0
• Analysis capability (3)	2	2	4	4
• Constraint checker (1)	2	5	1	0
• Automation capabilities (1)	2	2	5	5
• Future prospect (1)	4	4	4	2
• User guidance (2)	5	1	2	1
• Multidisciplinary modeling (2)	4	4	4	2
• Interaction with *iDAM* (3)	2	4	5	3
• Interaction with *GeneSys* (3)	2	2	5	3
• **Total**	123	127	136	115

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Kevin Robinson et al. continued from page 45

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Applying a System of Systems Perspective to Hyundai-Kia's Virtual Tire Development

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ABSTRACT
Systems engineering has become important in almost every complex product manufacturing industry, especially automotive. Emerging trends like vehicle electrification and autonomous driving now pose a system of systems (SoS) engineering challenge to automotive OEMs. This paper presents a proof-of-concept (PoC) that applies a top-down SoS perspective to Hyundai-Kia Motor Corporation's (HKMC) virtual product development process to develop a performance-critical component of the vehicle, the tire. The PoC demonstrates using the Arcadia MBSE method to develop a consistent, layered, vehicle architecture model starting from the SoS operational context down to the lowest level of system decomposition in the physical architecture thereby capturing top-down knowledge traceability. Using the concept of functional chains, several vehicle performance views are captured that serve as the basis for architecture verification orchestration across engineering domains using a cross-domain orchestration platform thereby validating key vehicle/tire performance metrics that influence the tire design parameters. Preliminary results of the study show that applying a method-based modeling approach could provide several benefits to HKMC's current product development approach such as reduced time to model, SoS knowledge capture and reusability, parameter/requirement traceability, early performance verification, and effective systems engineering collaboration between the OEM, tire design supplier, and tire manufacturers.

INTRODUCTION

With recent developments in electric vehicle and driver assistance technologies, the automotive product development landscape has changed significantly over the past decade. The modern car as we know now is a highly complex system that comes with somewhere between 70 and 100 electronic control units (ECUs) that control most of the vehicle's functions and over 100 million lines of code that make up all the vehicle's software (Mihailovici 2021). An addition to this trend has been the dramatically changing context of the vehicle's operating environment. With increasing emphasis on limiting the environmental impact as well as enhanced driver safety, the need for ramping up the civil infrastructure to meet the vehicles' operational demands is evident. Smart energy grids, 5G-enabled communication networks, smart parking systems that will require vehicle-to-grid (V2G), vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technology interfaces are just few of the many operational environment constraints that will drive automotive product development in the coming decades (Varanasi 2022, Litman 2022, Bhatti et al. 2021). Compared to the traditional systems engineering viewpoint, where product development is seen as a system engineering problem, the approach must evolve where developing a vehicle must be seen as part of a bigger mission that consists of disparate systems that interact with each other to deliver a common mission or a capability. Particularly, developing an electric vehicle with advanced driver assistance systems can no longer be looked at as an isolated product development problem. Add to that the regulatory complexity that will arise from urban mobility systems which can easily render current product development approaches unscalable (Freemark et al. 2022, Eugensson et al. 2013).

Looking at the other side of the problem, the vehicle performance needs are equally, if not more important to provide a safe and sustainable quality product to future consumers. With changing user needs, every new vehicle program presents numerous challenges such as managing significantly higher variations in the product lines, minimizing development risks and costs, reduced cycle times, to name a few, while ensuring that the product meets its optimum performance targets. In the case of autonomous driving, occupant safety is one of the most crucial drivers in technology development. To that effect, tire manufacturers are already analyzing the emergent impact of smart, intelligent tires to realizing safer autonomous mobility solutions with highly promising possibilities (Continental 2022). This implies that every changing user need may impact operational mission needs which cascade down to the individual subsystem and component requirements including their performance and design constraints. Not only systems, but the way their constituent subsystems and components are designed and managed in an enterprise needs to be more efficient to meet current product development timelines. Automotive manufacturers have become wary of this trend and have begun investing heavily into evolving their product development approaches, moving from a document-based to a model-based paradigm. HKMC acknowledges this trend and has committed to developing next-generation engineering and product data management environments for digital mobility transformation (Siemens 2021). From a system engineering standpoint, this clearly presents a 'system of systems (SoS)' challenge. According to the INCOSE SoS primer, a SoS is a collection of independent systems, integrated into a larger system that delivers unique capabilities. The independent constituent systems collaborate to produce global behavior that they cannot produce alone (INCOSE 2018). Following this definition, in this proof-of-concept (PoC), we apply a SoS perspective to HKMC's virtual tire development process. The scope of the project is to develop a purpose-built vehicle concept architecture that can:

1. Provide a descriptive reference of the SoS context, its constituent vehicle's functions, structure, and interfaces,
2. Enable early vehicle/tire performance verification based on predefined metrics and,
3. Enable system-to-subsystem collaboration with downstream subsystem and component designers/architects through a cross-domain collaboration platform.

Right from the beginning of architecture development, the SoS perspective is applied to the virtual tire development process such that the development of the independent constituent system, the purpose built vehicle (PBV), which is the electric vehicle is seen as a key contributor to achieving the higher capability of the SoS. Once the SoS problem domain is established, we present a methodological approach to develop the constituent PBV using a modular vehicle architecture concept, iteratively and recursively decomposing down to the tire component, the design of which is the goal of the study.

(a) (b)

Figure 1. Purpose built vehicle concept (Hyundai Motor Group TECH)

Purpose Built Vehicle (PBV)

Purpose built vehicle (PBV) is Hyundai Motor Group's eco-friendly, multi-purpose mobility vehicle solution that can be provided at low cost and is intended to meet customer's business purpose and needs (Hyundai 2021). It is a modular device with a simple structure whose design can be adapted to changing customer demands and business requirements. An important aspect of the PBV mission is to provide solutions to increase customer business value and maximize the efficiency of business operations. PBV devices can span from 3m to a maximum of 6m in length based on an expandable architecture (skateboard platform) and can respond quickly to various business and customer UXs in mobility, logistics, living space, etc. In addition, if combined with autonomous driving technology in the future, it can be used as a robot taxi or unmanned cargo transportation. Figure 1 (a) and (b) show examples of the PBV concept. Applying the MBSE approach to PBV development is expected to capture PBV knowledge in a layered modular architecture at different levels starting from the SoS context down to the physical component description, with traceability to different levels of requirements and parameters. The architecture shall include descriptive performance knowledge that captures key vehicle performance concerns such as ride and handling, durability, mileage, NVH (noise, vibration, and harshness) and low rolling resistance co-efficient. After several iterations of architecture definition and verification, the PBV architecture is expected to capture critical performance details including the functionality specification with performance metrics and optimum component design parameters along with requirement traceability. This knowledge once captured is expected to be reusable across projects and programs potentially leading to significant process improvements.

Virtual Tire Development

In response to growing environmental concerns, the United Nations Economic Commission for Europe (UNECE) enacted the worldwide harmonised light vehicles test procedure (WLTP), a vehicle performance measurement standard, and continues to discuss environmental and energy-related vehicle regulations. CO2 emission regulations greatly influence the overall automotive industry towards which it is developing sustainable solutions (UNECE 2014). It has been reported that a 10% reduction in a vehicle's rolling resistance can reduce CO2 emissions by 1.5-2.0% (Riemersma and Mock 2012) and provide about 1% improvement in fuel economy (Barrand and Bokar 2008). Consequently, automotive suppliers have been developing low rolling resistance tires as a practical solution to improving vehicle fuel efficiency and reducing emissions. Also, vehicle tire characteristics are known to have a strong correlation with the various vehicle performances as tires provide the four main contact points between the vehicle and the driving surface. When tires are developed to objectively reduce rolling resistance to improve fuel efficiency, other performances of the vehicle such as ride comfort, handling, and noise, tend to deteriorate, especially for EVs, making it harder to deliver a quality product to the market.

Conventional tire development processes pose several limitations to developing newer vehicles like electric PBVs. For instance, batteries, an essential element of electric PBVs, increase the overall weight of the vehicle, and the electric motors generate high torque. This poses significant challenges to electric PBV tire development to satisfy the target performance requirements in harsh driving environments relative to tires designed for non-EVs. In the case of autonomous PBV, ride comfort performance needs may outweigh low tire rolling resistance needs. In other words, there are characteristics of newer electric vehicle parts and customer requirements that may go against the fuel efficiency targets (Koengkan et al. 2022, Weiss et al. 2020).

The traditional tire development process at HKMC was not suitable to address the modern PBV development challenges. Tire performance is optimized by focusing on vehicle-level performance targets. However, the multi-attribute performance goals cannot be satisfied simultaneously as they conflict with each other at the tire level. In the existing development process, tire performance development is performed mainly on real tires which makes it difficult to harmonize performance targets at the tire level and the vehicle level in the early development stages. In addition, tire is currently modeled as a black-box item at late development stages which is reused from previous vehicle programs resulting in a need to frontload tire engineering for new PBV during early vehicle performance development. To address these needs, a virtual tire development process using a virtual tire model has been established, that focuses on:

1. Adjusting individual performance targets at vehicle level
2. Dividing vehicle-level individual performance targets into tire level
3. Coordinating individual performance targets at the tire level.

As shown in Figure 2, in Phase 1, the vehicle level performance requirements (targets) defined during Architecture Gate 1 (AG1) are divided down to the tire level performance targets in Architecture Gate 2 (AG2). Virtual tire models (MF, MF-Swift, etc.) are used to determine optimum specification that can maximize the individual performances of tires in AG2. In the case of a tire, a particularly weak performance of tire is identified based on trade-offs. A standard tire specification is selected. Suppliers design tires that maximize individual performances based on the standard specifications. In this process, the functional tire characteristics (FTC) of the tire are evaluated using a virtual tire model based on the tire design parameter (TDP), and the harmonization performance of the tire is verified. By repeating this process in Architecture Gate 3 (AG3), a tire model that lacks performance compared to the standard specification is defined and vehicle level performance is verified. Finally, the real tire design is derived in Architecture Gate 4 (AG4). Currently, this architecture development approach to virtual tires uses multiphysics tire models that are developed in silos and are usually disconnected. Moreover, each individual performance engineer usually communicates separately with the tire simulation/design engineers that are usually from HKMC partner companies leading to inefficiencies in the virtual tire development process. There is an identified need for a robust and secure approach to enable efficient communication among development teams. A descriptive vehicle architecture that captures a consistent representation of the vehicle performances can provide a common source of vehicle performance knowledge that can be shared among the vehicle performance development teams, tire designers and eventually manufacturers in the later stages of the development life cycle that are usually located across different organizations. The paper describes an approach at HKMC that attempts to address these challenges.

The remainder of the paper is organized as follows: The second section provides a review of the literature around MBSE and SoS followed by an overview of the MBSE approach applied in this PoC study in the third section. The results of the

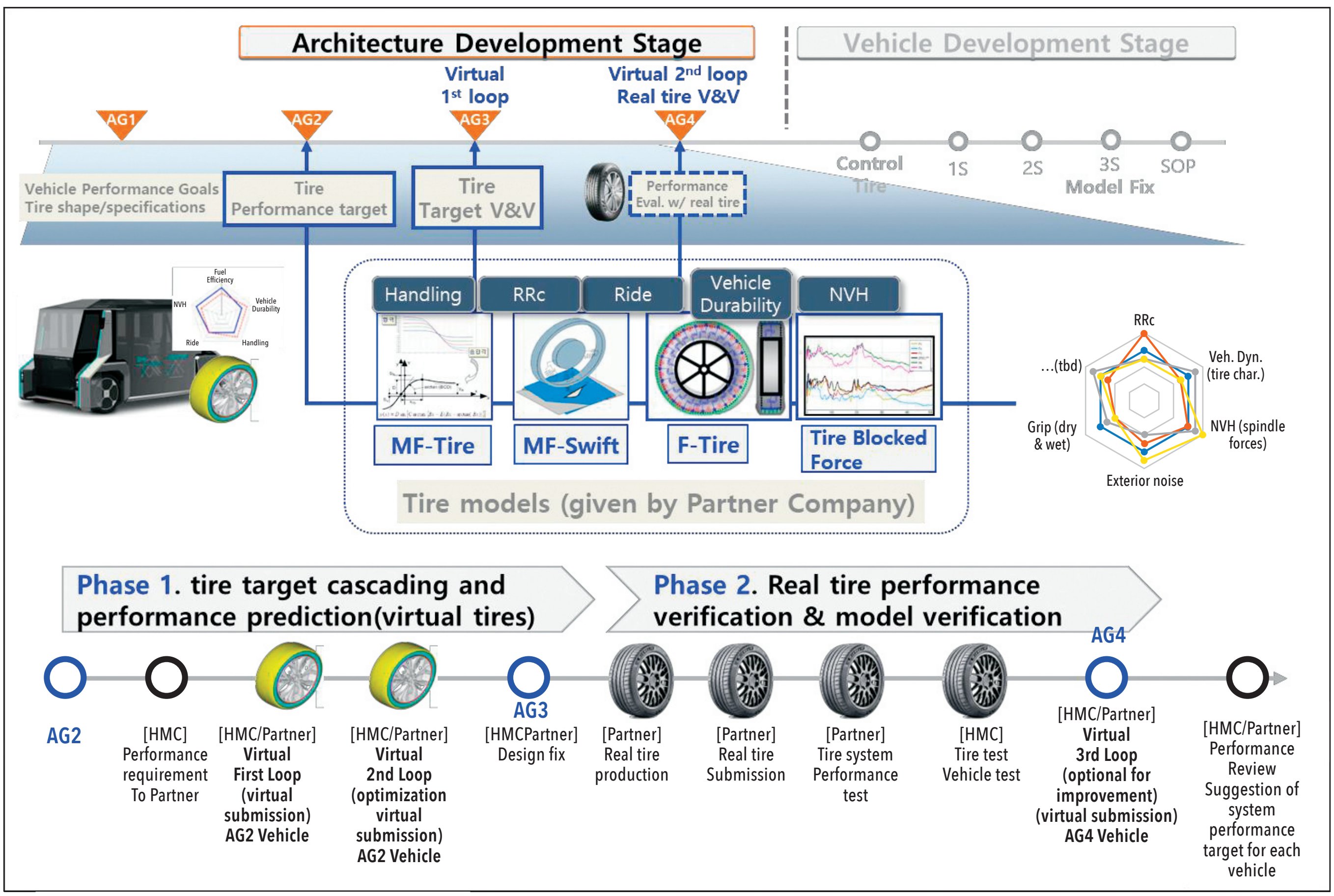


Figure 2. Virtual tire development process at HKMC (PBV 이미지 교체)

MBSE approach applied to virtual tire development are presented in the fourth section followed by conclusion and future scope discussion in the final section.

LITERATURE REVIEW

MBSE in Automotive

The INCOSE Automotive Systems Engineering Vision 2025 describes seven engineering challenges the automotive industry is currently facing and clearly signals the need of MBSE modeling as one of the many actions to realize the 2025 vision (INCOSE 2020). MBSE has become widely accepted across various product manufacturing industries and the acceptance is only growing. This has certainly contributed to the increasing literature available on the topic. Previous studies have suggested usage and implications of MBSE in the automotive industry. An overview of general challenges of implementing systems engineering and particularly MBSE across the automotive industry is provided where the authors describe the growing complexity of modern automobile systems as one of the major challenges for OEMs that pose the need for a model-based systems engineering approach. A system architecture model can serve a key role in managing risk and complexity by capturing various stakeholder concerns in a descriptive source while connecting that with broader engineering teams across the enterprise. In addition to describing the benefits of implementing an MBSE approach to automotive development, the authors also suggest that the overall complexity of modern automotive systems will soon require applying MBSE to the system of systems problem (Ambrosio and Soremekun 2017). The consistent academic and industrial pursuit in studying the breadth and depth of MBSE application across different stages of the system development life cycle has given insights not only into its potential for enterprise-wide benefits but also the increasing possibilities of using models as true sources of knowledge and decision-making. MBSE has been shown to incorporate product line engineering (PLE) through modeling variability in SysML models (Young et al. 2017). The authors present cases of feature based MBSE across three industries, where the automotive company uses a combination of MBSE and features models to manage the complexity arising from numerous product variations in today's vehicles. One of the main areas where MBSE is also seen as beneficial is the ability to manage simulations for multi-level requirements verification during the early concept stage. A descriptive system architecture can serve as a useful reference point to initiate multiphysics simulations of various subsystems and components to verify system-level performance requirements (Sohier et al. 2021, Nowodzienski and Navas 2022).

Not only OEMs, but also the global automotive supply chain has embraced the use of MBSE in transforming their heavily document-centric processes. In one such case, an automotive supplier for intelligent driver assistance systems has shown the use of a consistent system architecture model developed using the Arcadia approach across two operational projects with the objectives of improving efficiency and value for their customers, reducing development costs and schedule, fostering, and securing collaborative work and mastering complexity (Continental 2017). Their pilot MBSE implementations provided key insights into the benefits of using an MBSE approach, mainly better and effective communication with various stakeholders throughout the project's life cycle and have resulted in a wider acceptance across the enterprise followed by increasing numbers of the projects planning or already having deployed MBSE capabilities. Interestingly, the same group of supplier companies is one of the major vehicle tire suppliers to HKMC, which is the system component-of interest for this study.

System of Systems

System of systems engineering has been recognized as an MBSE focus-point in aerospace and defense industries based on the numerous references in systems engineering literature (Jamshidi 2008, DoD 2008). Great emphasis is placed on SoS as an emerging field in systems engineering necessary to respond to changing global contexts (INCOSE 2015). The 'ISO/IEC/IEEE 21839:2019 Systems and software engineering' standard provides critical SoS considerations that apply to a system that is a constituent system-of-interest (SoI) within an SoS, and that must be addressed at the key points in the life cycle of the SoI. These considerations can apply to man-made SoS whose constituent elements must include one or more of the following: hardware, software, humans, procedures, and facilities (ISO 2019). The systems in SoS have operational and managerial independence (Dahmann and Henshaw 2016) which make them very relevant in automotive companies that are expected to react at a rapid rate to the changing market needs while adhering to the requirements posed by future mobility SoS. Considering the modern automobile systems as constituent systems of a larger SoS, authors have provided recommendations on addressing automotive challenges by applying the SoS approach from an automotive OEM's perspective with limited authority over the other constituent systems forming the automotive SoS (Hoehne and Rushton 2018). Particularly, a modular open systems approach to automotive SoS is presented based on an existing transportation SoS framework of interoperability standards. The approach includes three key steps in modularizing any automotive SoS: *defining the technical modules* (infrastructure, energy, rolling stock and command, control and signaling) that the constituent vehicle directly interfaces with, *identifying the key vehicle interfaces* with the modules, and *specifying the interface requirements* which are further broken down into mechanical, electrical, communication, electromagnetic compatibility (EMC), and other applicable interfaces. Once modularized, these constituent systems can be developed and evolved independently without a common managerial authority. The technologies and teaming evaluation (TATE) framework is another example of a combined top-down/bottom-up approach to SoS comprising of manned and unmanned vehicles (Peters et al. 2018). The authors propose a modular and flexible approach to synthesizing and quantitatively evaluating configuration options within a SoS mission which can be further extended with various analyses that can aid in informing SoS and system requirements. Although SoS engineering and architecting is a challenging task because of the sheer complexity and scale of SoS, some attempts have been made to explore model-based methodologies and approaches to SoS architecting. The I^5 framework (interoperability, interconnectivity, interfacing, integration, and interaction) is one such approach that describes a model-based framework to design complex interactions among disparate systems, using object-process methodology (OPM) (Mordecai and Dori 2013). The framework provides an integration-centric perspective to SoS integration programs. OPM provides textual and graphical formalism to support the unique aspects in modeling and integration, such as capturing emergent properties and behaviors and a top-to-bottom hierarchy of interaction aspects among the constituent systems.

METHODOLOGY

Making the Case for EV Mobility SoS

In this PoC, the electric vehicle (EV) mobility SoS is defined as the operational context that drives the PBV development. The main constituent systems that provide EV mobility capabilities are the 'purpose built electric vehicle (PBV)', its interfacing systems such as 'smart energy grid' that includes smart charging stations, 'OEM' and 'eMobility service provider' that provides the charging station network and software services as shown in Figure 3.

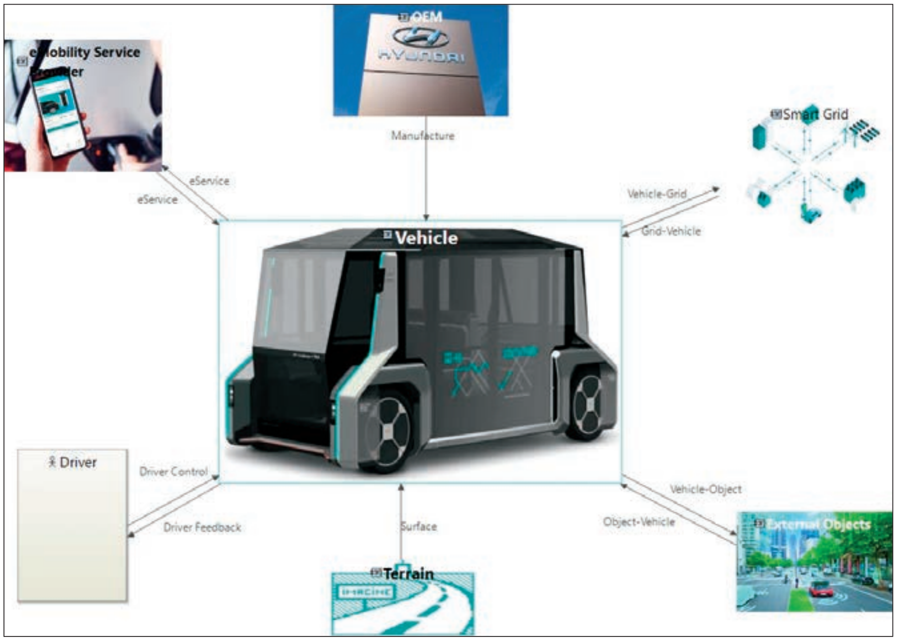


Figure 3. EV mobility SoS: operational context in Arcadia (PBV 이미지 교체)

Each of these systems are defined as modules that serve individual purpose(s) towards delivering the EV mobility mission. Because of the complexity and regulatory challenges noted in the introduction, HKMC believes that the most effective way to address the EV mobility challenge is by implementing a modular SoS approach that is supported with a robust underlying MBSE method. Such an approach will provide a strong MBSE foundation to the future mobility blueprint initiative laid out by HKMC (Hyundai 2022). It is therefore important to justify the case for EV mobility as an SoS problem. To do so, we look at the five main characteristics of SoS as defined by Maier (1998):

1. **Operational independence**. Each constituent system in an SoS must be able to operate independently of the SoS and the other systems. While the electric vehicles rely on external charging networks and services for high mileage, their operational independence does not require new development of every constituent system which may already exist and can rather be called upon to support a new capability.
2. **Managerial independence**. In addition, each constituent system in SoS is managed independently. With growing demands for EV technology and emerging interoperability standards, products must evolve rapidly to respond to these changing needs. The OEMs for EVs will continue to independently develop and evolve products while adhering to the SoS operational constraints whereas the energy management grids will evolve to respond to growing energy efficiency requirements.
3. **Geographical distribution**. SoS consist of geographically distributed systems. The EV, charging systems, smart grids, and mobility systems are geographically distributed.
4. **Evolutionary development processes**. SoS development is incremental as the constituent systems develop and evolve incrementally and/or asynchronously. The evolution of the EV mobility SoS is derived from the evolution of EV technology which may be more frequent in delivering constituent system capabilities.
5. **Emergent behavior**. SoS exhibit emergent behavior that results from the relationships and interactions between the constituent systems. In EV mobility SoS, each constituent system has a well-defined purpose. The EV must provide a transportation vehicle powered by electricity, the smart grid provides efficient energy generation and distribution to the electrical charging stations while the mobility services provide vehicle connectivity to communication networks for driver assistance, all leading towards the emergent behavior of reducing global carbon emissions.

MBSE Process Orchestration

This section describes the model-based systems engineering (MBSE) approach applied to the virtual tire development process at HKMC, which includes three major elements as shown in Figure 4:

1. **System Architecture Authoring**. Based on the requirements captured in a requirements repository, a concept architecture is used to describe the SoS operational context and the PBV architecture. The vehicle architecture modeling is significantly influenced by the vehicle's functional and non-functional constraints posed by the vehicle requirements which are then associated to the architecture elements. System Modeling Workbench (SMW) for Teamcenter® is used as the primary architecture authoring tool in this study. SMW is an integrated systems modeling environment that is used to apply MBSE concepts to the architecture development process using the Arcadia method.

   Architecture analysis and design integrated approach (ARCADIA) is a system and software architecture engineering method, based on architecture-centric and model-driven engineering activities (Voirin 2017).

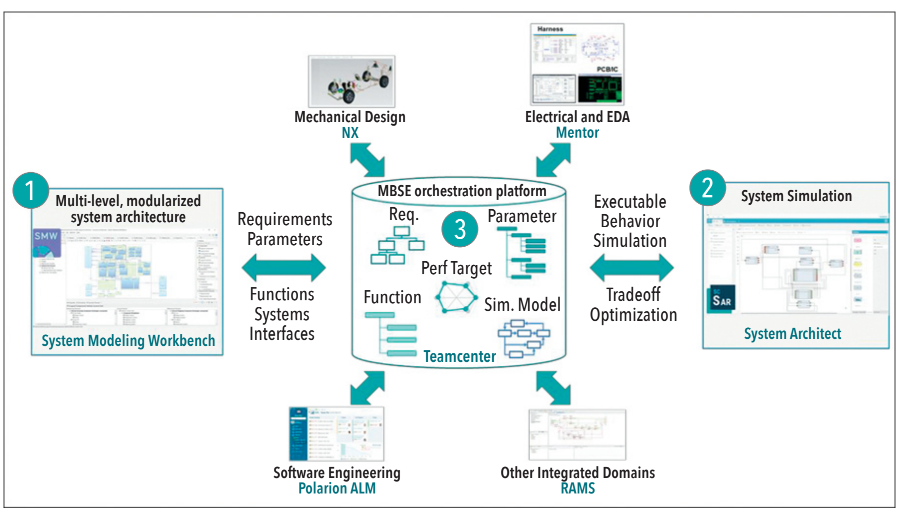
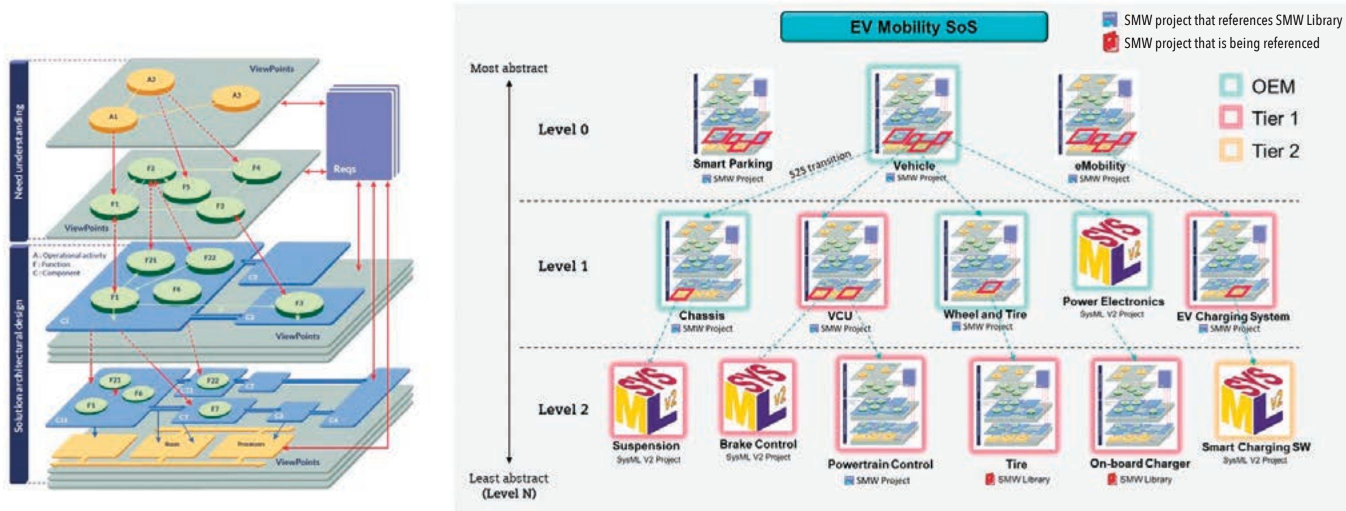


Figure 4. MBSE process elements



(a) The Arcadia method (b) SoS modularization and classification

Figure 5. Applying the Arcadia method to EV mobility SoS

The Arcadia method shown in Figure 5 (a) provides a layered approach to modeling multiple levels of vehicle architecture at varying layers of abstraction, mainly *operational needs analysis (OA), system analysis (SA), logical architecture (LA) and physical architecture (PA)*, which is then orchestrated across engineering domains through an MBSE orchestration platform. Following the rationale for SoS, the Arcadia method is applied to model a multi-layered modular electric vehicle architecture that operates in the SoS context. Figure 5 (b) shows the EV Mobility SoS modularization concept that focuses on defining the SoS modules in Arcadia while independently managing their lifecycles through the orchestration platform. For this study, the focus is to define only the 'vehicle', 'wheel and tire' and the 'tire' modules, whereas the definition and management of other modules across all the levels is not part of the scope. The approach also takes into consideration the future of system modeling languages, including the upcoming SysML V2 specification (Bajaj et al. 2022), exploring possibilities of interoperability between Arcadia models and SysML V2 specification models, which is currently supported in SMW (Beta).

2. **System Simulation**. A multidisciplinary system simulation software is used to perform vehicle-level performance synthesis. This provides a means to verify the vehicle's key performance metrics early in the concept stage. The performance simulation is driven by metrics defined in the concept architecture to evaluate the vehicle dynamics and provide the best set of tire design parameter values which are then captured as configurable objects in a common database. Simcenter System Architect® is used as the multiphysics simulation software to analyze the vehicle performances.
3. **MBSE Orchestration**. Siemens Teamcenter® is used as the cross-domain platform in this study that enables the orchestration of the overall MBSE business process. In addition to providing model lifecycle management capabilities, the platform also enables managing granular architecture and simulation data and model files, parameters, requirements and creating cross-domain verification requests and workflows to facilitate multidisciplinary analysis and optimization. The MBSE orchestration platform provides the ability to share architecture models as whole and in parts with various stakeholders with granular traceability to numerous model elements, which is key to enabling the model-based workflows. The platform also provides the primary requirement and parameter authoring capabilities and traceability to the concept architecture elements which enables granular cross-probing across the system's RFLP definition, also called the *integrated system definition*.

MBSE Approach Applied to HKMC's Virtual Tire Development

This section describes the MBSE approach applied to HKMC's virtual tire development process as overlaid on the left-side of the V-diagram in Figure 6:

1. **Requirements and Metrics Definition**. As described before, the MBSE orchestration platform is used to author various levels of requirements starting from the SoS stakeholder needs all the way down to component design requirements. The SoS operational context captures the numerous constituent systems that

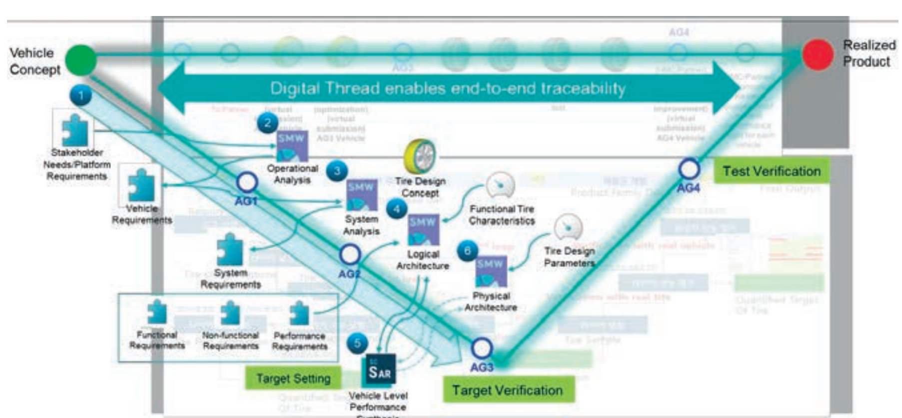


Figure 6. MBSE approach applied to HKMC's virtual tire development

have their own sets of requirement specification that may be captured in the same environment depending on the 'managing authority' for those systems. Along with requirements, various levels of metrics and design constraints such as the FTC/TDP are captured in the same repository. The requirements and parameters are configurable objects that are linked to the various layers of the architecture model elements that are also shared across various domain assets managed in the cross-domain platform. This step usually starts early in the SoS concept exploration phases and is carried throughout the PBV concept development stage. In this study, the main drivers were the high-level stakeholder needs and platform requirements for the PBV.

2. **SoS Context and Operational Analysis (OA)**. The Arcadia OA layer is used to model the operational context of the SoS, capture the stakeholders, describe the SoS capabilities and high-level operational scenarios. The operational analysis results in identification of artifacts such as capability objectives, concept of operations (ConOps), and refined vehicle requirements specification that capture the stakeholder expectations. In other words, the vehicle requirements represent what the stakeholders expect from the 'to-be developed' system. This step is executed before AG1 in the virtual development process.
3. **System Analysis (SA)**. The Arcadia SA layer follows AG1 and is used to establish the PBV context as the SoI and define the functional dataflows and behavior along with the system boundaries. We modeled the functionalities of the performances using '*functional chains*' which describe the functional flows required to achieve desired capabilities. Functional analysis is the iterative and recursive process of identifying the functions that a system must perform to achieve the desired behavior, decomposing the system-level functions into their lowest level and defining relationships between the functions (Voirin 2017, Kossiakoff et al. 2020). The system functional analysis, executed before AG2, results in refined system functional and non-functional requirements that are captured in Teamcenter.
4. **Logical Architecture (LA)**. The Arcadia LA layer allowed us to capture the vehicle's logical systems and their interfaces that will deliver the required functional behavior, simultaneously capturing the tire design concept as parametric requirements in Teamcenter. The vehicle and tire-level FTCs are refined and scoped to the architecture project for the study and associated to the architecture elements. The *functional chains* enable creating functionality-specific views of the logical architecture that are useful to communicate the system architect's functional intent with the simulation engineers along with the associated vehicle requirements. This step is followed by AG2 and AG3 for multiple virtual verification loops.
5. **Architecture Verification.** At this point, early vehicle performance verification is initiated from the logical architecture where the FTCs for each performance area are linked. The performance of the vehicle is verified using multiphysics simulation by qualifying the FTC targets and a set of optimum TDPs is selected. The verification is orchestrated with the help of the Verification Request feature in Teamcenter that enables capturing all the relevant datasets pertaining to the simulation, including architecture model views and granular model objects, simulation parameters and simulation models conveniently packaged at the simulation engineer's disposal. The simulation engineer performs vehicle performance simulation to evaluate the FTCs and provides the TDPs in response to the verification request.
6. **Physical Architecture (PA)**. The Arcadia PA layer is used to identify and select technology choices for the logical subsystems and components, which can then be used to relate the design parameters such as the TDPs. The transition between the logical and physical layers is performed simultaneously with the orchestration of the verification request. For a smoother collaboration between the system architects, subsystem architects and designers, Arcadia 'system-to-subsystem transition' was used to demonstrate a case of carving out a part of the vehicle's logical architecture to be shared with the simulation engineer/designer such that the designer can access only the part of the architecture to which the design parameters must be associated. This facilitates robust and secure data sharing among participants in the systems engineering workflow. To the effect of establishing end-to-end traceability, the *operational processes* defined in the OA layer are traced to the *functional chains* in the SA, LA and finally the PA layer that capture the physical design constraints. Such traceability can enable analyzing the impact of changing SoS operational needs to the physical design details of its constituent system modules for a faster development response.

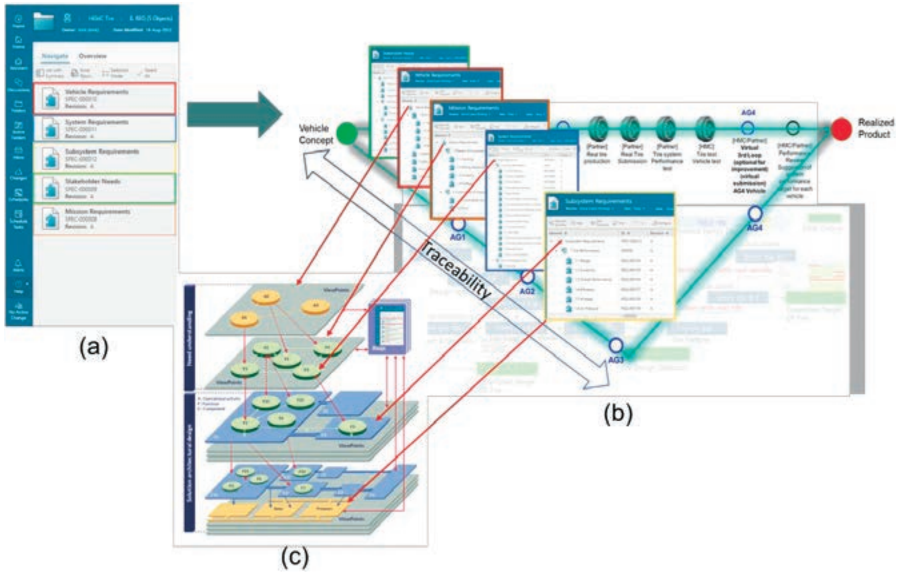


Figure 7. Requirements definition throughout the virtual tire development process

RESULTS

Requirements and Metrics Definition

Figure 7 (a) shows the various layers of requirement specification captured in Teamcenter®. Starting with the high-level needs, the SoS needs were captured in the form of need statements into configurable requirement objects in the stakeholder

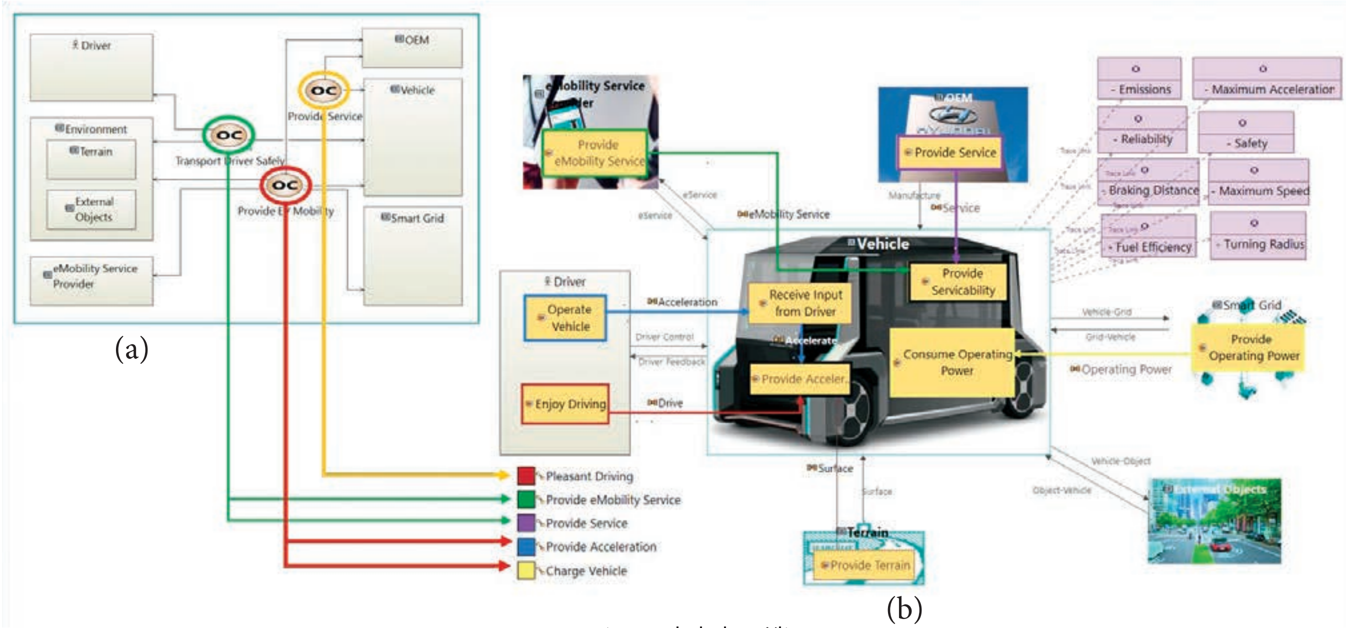


Figure 8. *SoS operational analysis using Arcadia OA layer* (PBV 이미지 교체)

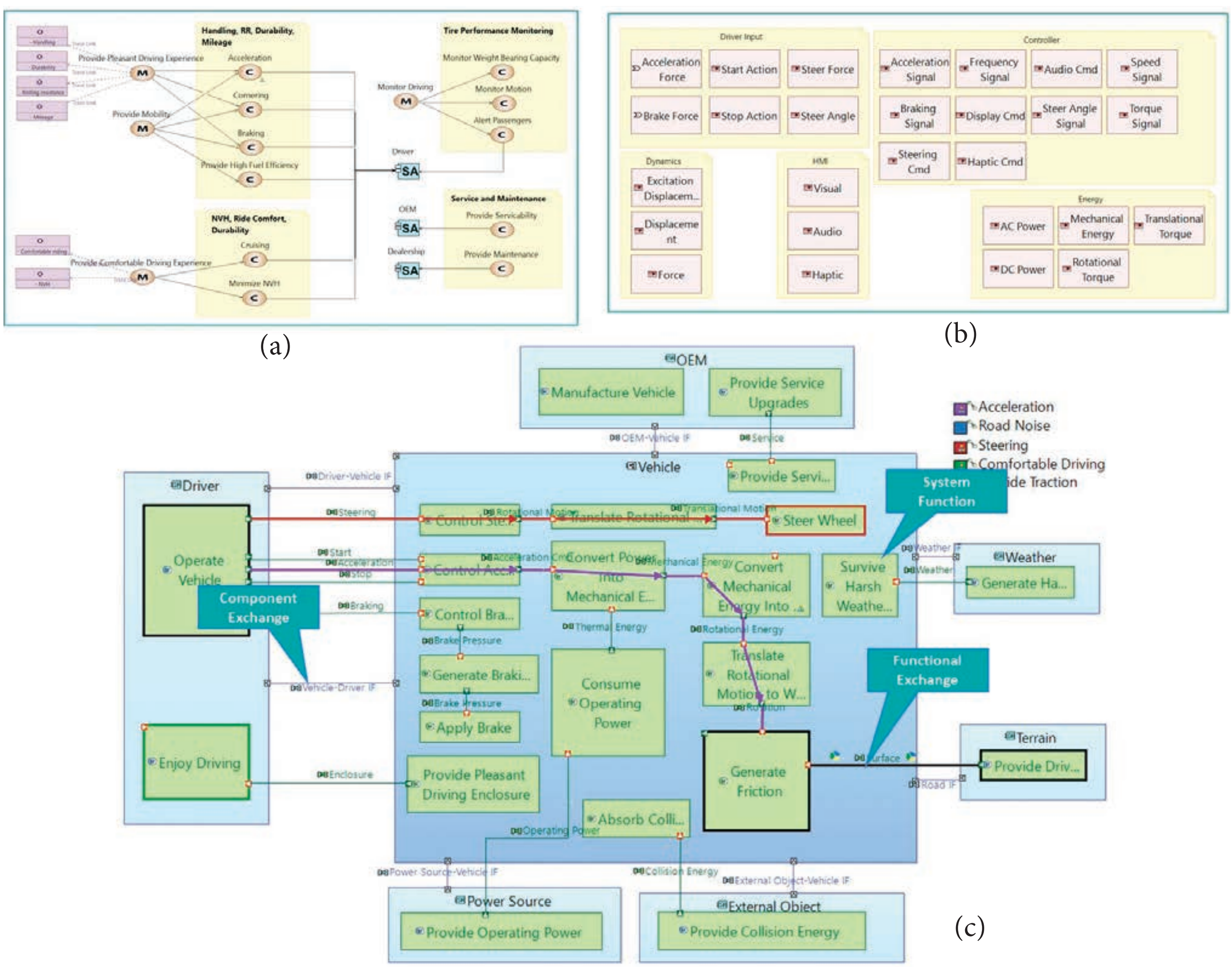


Figure 9. *System mission and context analysis using Arcadia SA layer*

requirements specification. The mission requirement specification captures the PBV mission in the context of the SoS thereby leading to operational analysis. The operational analysis resulted in clearly eliciting the vehicle requirements specification that captures the to-be developed PBV concept, including key measures of performance (MoP) such as *maximum acceleration, maximum speed, turning radius, braking distance*. This provided a basis to perform system analysis where vehicle was contextualized as a black-box entity, resulting in blackbox functional analysis to identify the key system-level functional (and non-functional) needs that are then captured in the system requirements specification. The system requirements specification includes requirements that also capture the key performance metrics (FTCs) that are eventually associated to the logical architecture view describing the vehicle performance functionalities namely, *ride comfort, handling, NVH, durability and rolling resistance*. The logical and physical architecture layers result in the subsystem requirements specification that capture the design requirements for the subsystems. For this PoC, the focus was on eliciting only the tire design requirements. Figure 7 (b) shows the requirements specification flow down along the HKMC virtual tire development process between the architecture gates and Figure 7 (c) shows the Arcadia method and its different modeling layers at which the requirements are linked to the architecture model elements. As described previously, the requirements definition process is applied throughout the modeling activity to achieve requirements flow down, and traceability is established with the model at desired levels.

SoS Context and Operational Analysi

Figure 8 (a) shows the *operational capabilities blank* diagram that captures the operational capabilities of the SoS, mainly 'provide EV mobility' and 'transport driver safely', which includes sub capabilities such as 'provide acceleration', 'provide pleasant driving experience', 'provide comfortable driving experience' that are hidden for simplicity. One of the main benefits realized during the architecture development in Arcadia was the ease of creating multiple views to represent several aspects of the same integrated model. Figure 8 (b) shows the *operational architecture blank* diagram that describes the operational context of the SoS. The operational architecture shows the allocation of a selected set of *operational activities* to the constituent *entities* and *actors* of the SoS and their *activity interactions* that capture the high-level dataflow between the activities. This view provided a high-level understanding of the operations that the SoS stakeholders expect from the constituent systems and actors to achieve the SoS capabilities. It also shows the *operational processes* 'charge vehicle', 'provide acceleration', 'pleasant driving', 'provide service' that describe the operational behavior required to achieve the SoS capabilities. As a result of the operational analysis, the PBV requirements were captured to specify the vehicle concept and traced to the operational architecture.

System Analysis

Figure 9 (a) shows the *mission capabilities blank* diagram that describes a subset of the vehicle's *mission* and the desired *system capabilities*. The PBV is expected to provide *system capabilities* that support the *missions* 'provide mobility,' 'provide pleasant driving experience' and 'provide comfortable driving experience' that realize the *operational capability* 'transport driver safely.' The *system architecture blank* diagram (also called system context/black box diagram) is shown in Figure 9 (c) which shows the primary functional allocation to the system and the system actors mainly, 'driver,' 'charging station,' 'weather,' 'external object,' and 'terrain.'

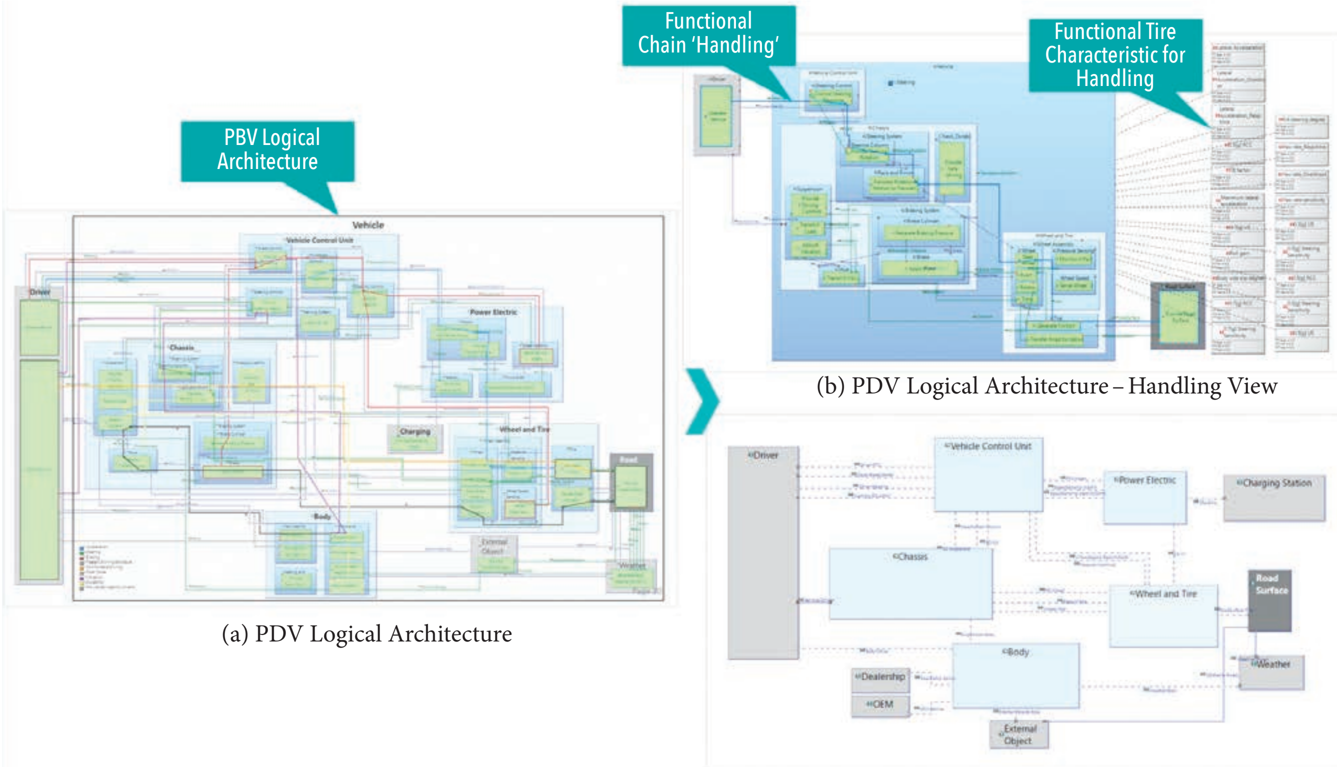
The system architecture shows an integrated view of the *functional interactions* and the system's external interfaces that carry the functional dataflow shown in Figure 9 (b), which consists of matter, energy and/or data. One of the main purposes of the modeling activity was to capture the vehicle behavior that affects the performances: *handling, rolling resistance, durability, NVH* and *ride comfort*, which are represented using the color ed *functional chains* as shown in Figure 9 (c). Other diagrams for system analysis that were developed for this study included the *system functional data flow* diagram, to capture the global functional dataflow expected from the system and its actors, *mode and state machine* diagram to capture the vehicle states, and automatically generated views such as *system function breakdown* diagram to represent the global functional breakdown and *exchange scenario* diagram to describe sequential flow of functions that describe the functional behavior. The SA layer in Arcadia efficiently supports the system functional analysis and the activities required by the system requirements definition process as described in the INCOSE *Systems Engineering Handbook* (INCOSE. 2015).

Logical Architecture

The *logical architecture blank* diagram is shown in Figure 10. The *system functions* defined in the SA layer were allocated to the *logical subsystems* and *components* in the LA layer as shown in Figure 10 (a). Most of the functional architecture defined in the SA layer was automatically transitioned into the logical elements thereby reducing significant rework. The key *logical subsystems* identified include the 'vehicle control unit', 'chassis', 'power electric,' 'wheel and tire' and 'body.' These subsystems and their *logical interfaces* represent the logical breakdown of the PBV and their allocated functional behavior. The 'wheel and tire' subsystem remains the key focus of project as the objective is to simulate the vehicle performance to capture the best set of design parameters for the vehicle tires (TDPs). Based on a consistent logical architecture definition, several simplified functionality-specific views expressing a particular stakeholder concern are generated using SMW diagram filters to communicate the architecture design between the various stakeholders involved in virtual tire development. Figure 10 (b) shows the functionality-specific view representing the *handling* performance and a tailored simulation-specific view (simulation concern) that enables communicating the logical architecture schematic to the system simulation engineer is shown in Figure 10 (c). The FTCs related to the *handling* performance are linked to the 'vehicle' block in the functionality view. The 2 views provide the basis for the simulation engineer to analyze the system performance with the goal to identify the optimum TDPs for the 'tire' component. Similar functionality specific views were generated for *ride, NVH, mileage*, and *durability* with their corresponding FTCs associated to the 'vehicle.'

Architecture Verification

Teamcenter® Verification Request encapsulates the verification process inputs mainly verification requirements, FTCs, system architecture models, test methods, test cases, simulation input/output parameters, etc. to effectively communicate verification request criteria and procedures to the domain experts. The logical architecture imported into the simulation environment provides a modifiable simulation architecture skeleton as the starting point as shown in Figure 11. A simplified logical architecture view of the vehicle was generated for the purpose of simulation with only the level 1 subsystems required to develop a physics-based simulation model. With the help of simulation libraries, physical systems are assigned to each subsystem/component such as the VCU, chassis, power electric, wheel and tire and body and a system simulation model is developed for each scenario with corresponding physical components, as different sets of boundary conditions (driver and road) and tire models are considered to extract FTCs and identify optimum TDPs.

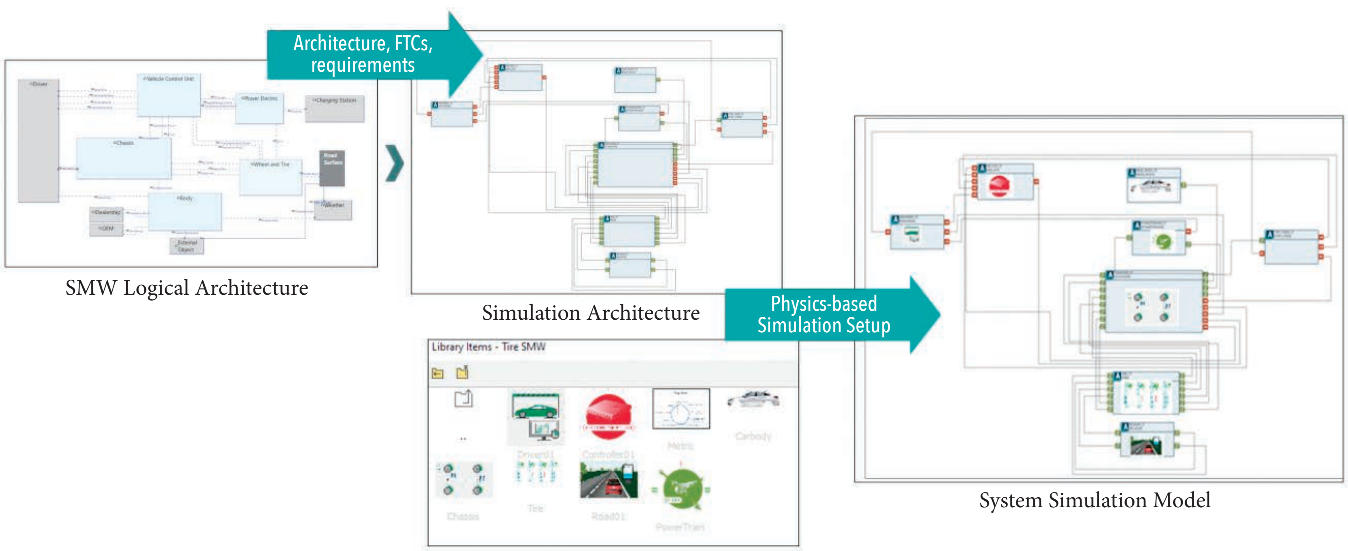


(a) PDV Logical Architecture

(b) PDV Logical Architecture – Handling View

(c) Logical Architecture – Component View

Figure 10. Logical architecture and FTCs



SMW Logical Architecture

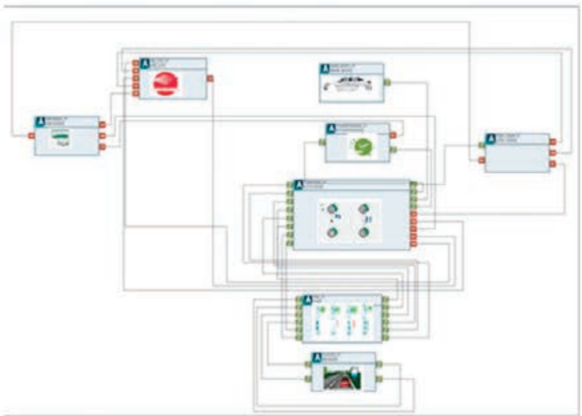
Simulation Architecture

Physical Systems Library

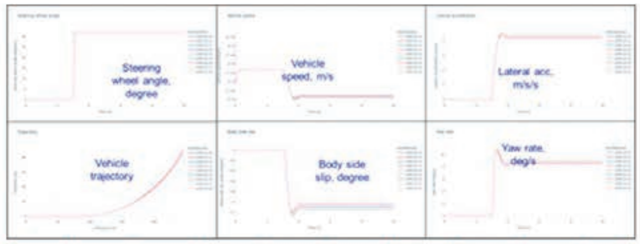
System Simulation Model

Figure 11. Transitioning From system architecture to simulation model

For this study, 'step steer' and 'constant radius' scenarios are simulated on flat road with 'Pacejka tire' model (Pacejka and Bakker 1992) to evaluate the handling performance whereas 'ride' scenarios are simulated with rough road and 'F-tire' model (Gipser 2003). For step steer, handling simulation architecture model is evaluated with constant speed of 100 kmph and step input of steer angle to achieve target 0.4g (4 m/s/s) acceleration to extract lateral acceleration and yaw rate. Similarly, vehicle performance evaluation for 'virtual turning' (constant radius cornering) and 'ride' scenarios was performed to extract the corresponding FTCs. Once the desired verification targets are achieved, the output parameter values are updated in Teamcenter and are synchronized with the system architecture model for updated traceability. Postprocessed simulation results as shown in Figure 12 were obtained for 9 different architecture choices and the optimum parameter set is baselined in Teamcenter to capture the TDP values. Simultaneously, the values of the extracted FTCs are saved to Teamcenter and synchronized with the parameters traced to the logical architecture in SMW for baselining. Such an integrated verification mechanism can enable efficient collaboration between the system architects and simulation engineers by providing a common dashboard for verification enabling real-time visibility to verification teams across the enterprise thereby improving the verification process efficiency.



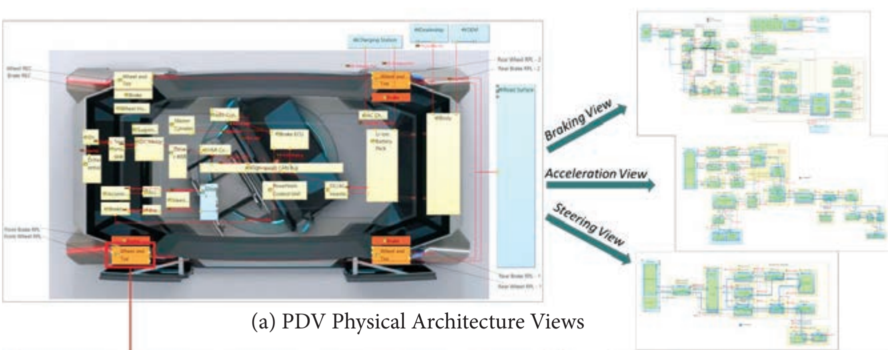
(a) Simulation Model



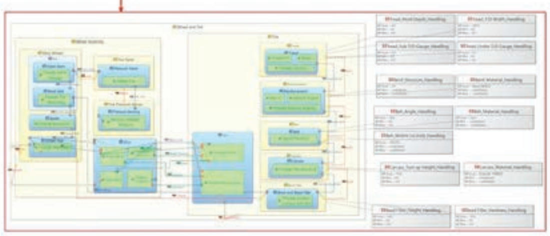
Architecture	Yaw rate overshoot, %	Yaw rate response time, s	Lat acc overshoot, %	Lat acc response time, s	0.4g steering angle, deg	Yaw rate sensitivity, deg/sec/100deg	Roll gain, deg/g	Body Sideslip, deg	TB factor, deg*sec
1	25.44	0.08	4.62	0.19	32	27	0.08	1.05	0.28
2	24.05	0.08	4.51	0.19	32	27	0.07	1.09	0.32
3	23.26	0.08	4.41	0.19	32	28	0.07	1.14	0.34
4	23.23	0.08	4.41	0.19	32	28	0.07	1.14	0.34
5	25.44	0.08	4.62	0.19	32	27	0.08	1.05	0.28
6	24.17	0.08	4.51	0.19	32	27	0.07	1.09	0.32
7	24.19	0.08	4.52	0.19	32	27	0.07	1.1	0.31
8	23.15	0.08	4.41	0.2	32	28	0.07	1.15	0.34
9	25.59	0.08	4.62	0.19	32	26	0.08	1.05	0.28

(b) Post-processing results

Figure 12. System simulation results and FTC extraction



(a) PDV Physical Architecture Views



(b) Physical Architecture—TDP for Handling

Part	Item (TDP)
Tread	T/D Width (mm)
	Mold Depth (mm)
	Under T/D Gauge (mm)
	Sub T/D Gauge (mm)
Reinf.	Material
	Structure
Belt	Material
	Width (1st/2nd) (mm)
	Angle (deg)
Carcass	Material
	Turn up Height (mm)
Bead Filler	Hardness (Hs)
	Height (mm)

(c) Tire Design Parameters

Figure 13. Physical architecture views and TDP

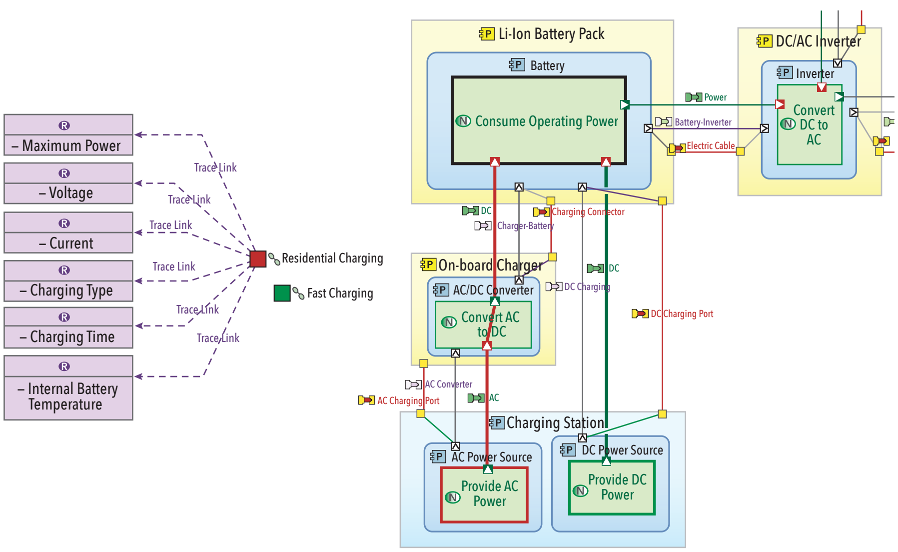


Figure 14. Physical architecture – 'Charging' view

Physical Architecture and Tire Design Parameters

Figure 13 shows some of the *physical architecture blank* diagrams developed in the PA layer. HKMC collaborates with a global supply chain to analyze vehicle's performance and share design data. The logical and physical architectures provide a means to collaborate with the design and manufacturing supply chain to exchange product information through a common source. The physical architecture diagram shows the selection of the *physical hosting components* that will deliver the desired vehicle behavior. Because of the sheer complexity of the vehicle architecture that results in the PA layer, it is difficult to capture the physical architecture in a single diagram, which is why a combination of different architecture views were developed resulting in one integrated model. Figure 13 (a) shows the simplified physical architecture diagram that includes the hosting physical components (wheel and tire, brake, DC motor, CAN bus, Li-Ion battery pack, etc.) that host the *behavior components* that realize the logical subsystems behavior along with several functionality-specific views describing parts of the overall physical architecture.

The system-to-subsystem transition concept demonstrated automatically transitioning from the 'vehicle' into a disparate model of the wheel and tire' module and the TDPs that are identified as a result of system simulation are captured in the physical architecture of the 'wheel and tire' module. This could potentially support model-based collaboration between the architects and the designers of a particular vehicle component, for instance the 'wheel and tire', without having the need to share the entire 'vehicle' architecture. Figure 13 (b) and (c) show the TDPs identified for the optimum *handling* performance whose values are captured and updated in the parameters linked in the physical architecture view for 'wheel and tire'. These values are synchronized with the parameter objects in Teamcenter once the architecture is baselined. Such a process allowed HKMC to capture the optimum parameter values in a single source that could then be viewed, managed and consumed by several stakeholders involved with the overall vehicle development. Finally, the physical architecture provides operational traceability to the lowest level of the modular SoS approach. As an example, the 'residential charging' and 'fast charging' *functional chains* shown in the physical architecture view in Figure 14 realize the *operational process* 'charge vehicle' that is one of the many processes required to deliver the 'provide EV mobility' SoS operational capability that was captured in the OA layer as shown in Figure 8. These chains capture the physical design constraints posed by the vehicle-to-grid (V2G) interfaces at the SoS level with traceability all the way to the PA layer in the form of physical design/interface requirements between the vehicle and other constituent systems thereby maintaining end-to-end traceability.

CONCLUSION AND FUTURE WORK

The PoC described in this paper shows how an MBSE approach can provide significant benefits to HKMC's product development process. The paper demonstrated the use of system architecture models managed in the context of a PLM-based orchestration platform enabling a digital thread as the basis of traceability across the MBSE enterprise. Considering the magnitude of challenges posed by the future of electric vehicle mobility, the study showed the possibility of applying a top-down, modular system of systems perspective to the problem of virtual tire development using a structured, method-based approach to system architecture modeling. A consistent system architecture model(s) can serve as a powerful tool to enable effective cross-domain communication across several stakeholders involved in the automotive product lifecycle. The ability to share and manage architecture lifecycle data through the orchestration platform allows to create an integrated system definition that can provide a common source of product information to several stakeholders involved in the MBSE processes. In addition to the commonly known benefits realized by an MBSE approach such as end-to-end requirement traceability and effective communication, HKMC's tire engineering team emphasizes the following benefits that are realized by using such an approach:

Reduced Time to Model. The Arcadia method guidance provided a structured approach to modeling the vehicle architecture with automated transitions between the abstraction layers and model validation capabilities. This resulted in an easier learning curve thereby significantly improving the time to model.

SoS Knowledge Capture. Modeling the operational context of the SoS using Arcadia can provide a richer understanding of the needs of all the stakeholders and constituent systems involved in the SoS. This helps in potentially extending the scope of possibilities that can be analyzed to meet the stakeholder needs before contextualizing the system boundary. The operational behavior and interfaces can be used to capture necessary *operational processes* that can result in better product planning decisions at the very early stages of product development. These processes are traced from OA to PA through the *functional chain*s. This can potentially enable tracing each individual SoS capability realization to the lowest level of the constituent subsystems and components that deliver the functionality.

Reusability. The concept of reusable libraries of model elements was explored to demonstrate reusability within the architecture project. This can result in a dramatic reduction in the architecture development effort. With increasing numbers of parts and components that compose the modern products, reusability across projects and programs will likely be a game changer as more engineering teams choose to adopt MBSE approaches in their respective development processes.

Parameter Management and Traceability. In vehicle performance development, one of the more pressing challenges faced by the Tire engineering team is the ability to efficiently manage and trace different levels of parameters that exist across the development lifecycle. Starting from the vehicle concept phase to the detailed design, the paper shows the usage of parameters as configurable objects used to specify vehicle and tire-level performance metrics (FTCs) and their traceability to the design parameters (TDPs) both in the context of the architecture definition activity. Not only did specifying FTCs enable easier communication between the system architect and the performance simulation engineer, but the ability to associate the TDPs to the physical architecture components provided a robust and secure way of sharing design data between stakeholders.

Early Verification. The parameterized logical architecture was used to initiate early system simulation for performance verification. This enabled frontloading design decisions and communicating physical architecture design with the domain engineers using a model-based reference provided by a modularized vehicle architecture.

Cross-enterprise Collaboration. Another perceived benefit of using MBSE is the ability to share whole or part of the system architecture with cross-domain teams. The case study demonstrated a system-to-subsystem transition approach where the 'wheel and tire' component in the physical architecture was transitioned into a separate Arcadia project that could be shared across the design teams with parameters flow down and capture design parameter values after verification in the physical architecture. This use case can potentially be extended to the Tier1/2 tire design and manufacturing suppliers with a robust and secure lifecycle management framework thus promoting a model-based enterprise.

This study presents tremendous opportunities to apply similar MBSE practices across HKMC. Future work should focus on establishing a complete modular vehicle architecture that can address numerous stakeholder concerns across the product development lifecycle. The system-to-subsystem transition addon in the modeling tool can facilitate generation of architectures of vehicle modules between levels and should be explored as a communication mechanism to share architecture modules with subsystem architects and suppliers through a robust collaboration framework, thereby enabling an extended MBSE enterprise throughout the design supply chain. The modularity should span across many architecture levels as shown in Figure 5 and each level shall include architectures that are reusable, maintainable and configurable. Future work should also focus on exploring the possibilities of connecting the architecture modules with the product variants library for better product planning decisions during future product evolutions. To realize a shared vision, the MSBE approach should be applied at scale across engineering teams and across other automotive companies such that a concept architecture defined at early stages provides a reference to downstream design teams with controlled access to architecture data for cross-disciplinary collaboration. ■

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Think Like an Ecosystem: Transitioning Waste Streams to Value Streams

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ABSTRACT
To meet the material demands of the future, transitioning waste streams to value streams is a vital step in ecological and economic sustainability. Linear production design disposes of resources before their optimal value have been realized and loses recyclable resources to waste streams. The economic infrastructure of the planet needs to be reimagined to meet human and ecological needs. The development and implementation of circular systems is key to the creation of sustainable global production. Through the analysis of the copper used in medical devices, we illustrate considerations systems engineers can take to close the waste-resource gap. Developing wasteless design mimics the resiliency seen in ecosystems and accelerates the evolution of the global economy to meet the needs of companies, the environment, and humankind.

INTRODUCTION

The Linear Growth Dilemma

The global economy functions on an assumption of continuous growth. The past century has been witness to unprecedented economic expansion with global resources being depleted at historical rates (Meadows et al. 2005). With linear expansion at the forefront of corporate initiatives, how does the economy expand infinitely on a finite planet?

The answer is a future-determining one. The economy simply cannot expand infinitely, and it will eventually hit its growth limit (Meadows et al. 1972). But solutions can be found by looking into the environments in your backyard. To the alpine tundra, the riparian valley, or the coral reef. These systems have persevered through planetary ages, evolving as the earth's ecological conditions changed (Boons 2013, Gamage and Hyde 2015).

What is their secret? Ecosystems survive because they are founded on efficiency (Boons 2013); there is no such thing as waste. Every product of an ecological process is re-integrated into the natural cycle. By reflecting ecosystems in human-designed systems we can facilitate sustainable resource use. In order to preserve the global economy, the systems we create must be wasteless. In a future with higher raw material demands, converting waste streams to value streams is necessary to maintain both economic and ecological prosperity.

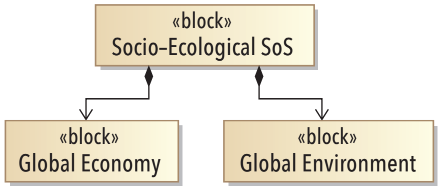

Figure 1. Statement of socio-ecological system of systems as the composition of the global economy and the global environment

The environment and the economy are intrinsically linked, rather than isolated cycles they are parts of the socio-ecological whole. Figure 1 defines a socio-ecological system of systems that comprises the global economy and the global environment. In this simplified view, the global economy is defined as a system of systems as demonstrated in Figure 2. The global environment block represents the bioregions, ecosystems, and their parts found on Earth. As materials are not yet harvested from extra-terrestrial sources, it is logical to assert that all materials used in the production of all goods and services are sourced from the global environment. Therefore, all waste that is not reused is destined to flow back to the global environment.

The global economy produces 2.01 billion tons of waste annually (The World Bank 2022). With this number growing with the increasing population, the quantity of wasted plastic, organic material, metals, elements, and minerals is projected to

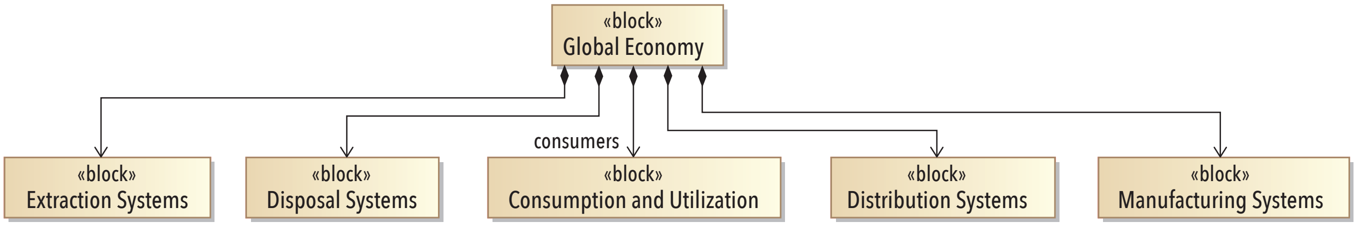

Figure 2. Definition of global economy as system of systems

increase by around 70% by 2025 (Romero-Hernandez and Romero 2018). The inefficient disposal of material contributes to the disruption of functioning ecosystems and fails to protect and maximize the investment of initial extraction. Environmental change has a direct impact on the efficiency and survival of humanmade systems (Boons 2013). By limiting our perspective to only the human designed system we leave out the critical impacts of the interfaces between the environment and the economy.

Figure 3 reflects the linear utilization schema where waste produced by the global economy flows back to the environment where it is neither reclaimed nor reused. By considering the environment as a stakeholder in our system development processes, it is possible to transform this linear flow into a sustainable circular flow by reprocessing and reusing the waste produced throughout the lifecycle of engineered systems. Reprocessing materials in many cases is less expensive and requires less energy than extracting new material (Gamage and Hyde 2012). By recognizing all waste streams eventually return to the environment as shown in Figure 3, systems engineers may expand the scope of their system boundary analyses to include the environment as an interfacing item and to identify the impact of the waste that results during each phase of a system's life cycle, including production, commissioning, utilization, maintenance, and decommissioning (Boons 2002). By considering the environment as a stakeholder, the scope of risk assessments should be expanded to explicitly assess environmental consequences of system designs.

Ecological-inspired design integrates human-demand into natural flows and sustainable cycling of resources through the environment (Gamage and Hyde 2012). Companies have the opportunity to increase value and resilience in their production cycles, and for stakeholders including the environment (Bocken et al. 2019). Transitioning to circular economies presents uncertainty, as it breaks away from the business models primarily used in the global economy. But it has the potential to evolve the infrastructure of commerce and create sustainable systems by optimizing revenue, shortening production cycles, and reinforcing economic resilience (Bocken et al. 2018).

When designing production cycles with society, environment, and economy in mind (Bocken et al. 2019) the definition of waste needs to be reevaluated. The economy and the environment must find a way to exist and still maintain ecosystem integrity through eliminating the need to deposit waste back into the environment (Geissdoerfer et al. 2017). By closing the gap between waste streams and value streams, production design can not only be more efficient but can regenerate the ecosystems they rely on for raw materials (Genovese et al. 2017).

Through discussion of the concept of waste, circular production design, and a case study using a medical device example that evaluates the impact of transitioning copper waste streams to value streams, we present a set of considerations that will aid systems engineers in integrating value streams into production systems.

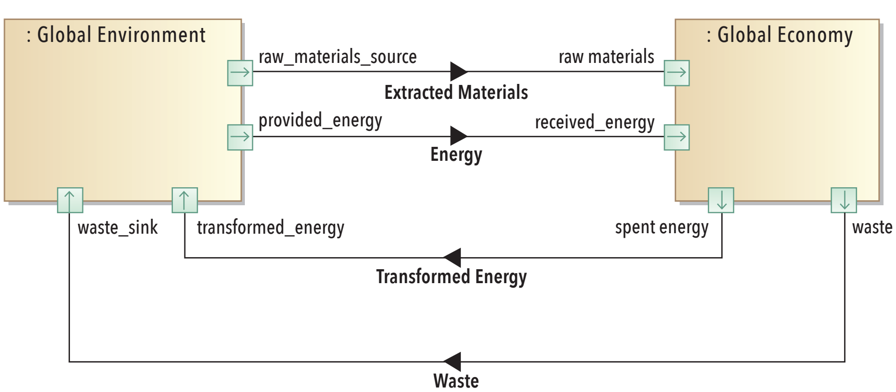

Figure 3. Major categories of interfaces between the environment and global economy

Waste Streams

The accepted standard for production and product design is linear. Resources are extracted as raw material from a natural environment, products are manufactured, the products are consumed, and then deposited back into the environment as waste. Waste is created and disposed of throughout this process, at the point of harvest and manufacture as well as at the end of the product's life. With every 20 tons of waste, there is an estimated 5 tons of waste produced during its manufacturing, and 20 tons eroduced at the point of resource harvest (Meadows et al. 2005).

In order to sustain the current demands of global production, ecosystem productivity is often exploited to meet economic needs. Though this is apparent across industries, elements and minerals present a particular point of concern because of their high demand in the modern economy for the construction of electronics (Northey et al. 2014). Element and mineral sources have slower rates of replenishment contributing to the added strain placed on the limited viable sources (the harvest point of a resource) (Meadows et al. 2005). While the limits of sinks (the destination of waste) are often considered, the limits of sources have a greater influence on the longevity of viable production (Meadows et al. 2013). When resources are harvested without sufficient time for the source to replenish, the usability of raw-material production is at stake (Boons 2013). With extended strain, these sources produce degraded and limited raw materials, which will impact the future cost of material extraction and refinement.

Increasing the sustainability of raw-material harvest should not be the only focus in reducing environmental impact. Redesigning production can further increase the sustainability of manufacturing (Bocken et al. 2019). These flows from sources to sinks, as shown in Figure 3, represent a linear model with a definite beginning and end. With production inevitably designed to produce waste and the majority of products being designed to end in landfills, resources are being returned to the environment long before their full value has been realized. This is strongly apparent in electronic waste streams, as the products contain metals, elements, and minerals. Not only are these materials relatively scarce but they also cause damage when introduced back into environments as waste (Bertram et al. 2002).

When linear systems are the norm, resources are lost to waste streams and reintroduced into the environment to disrupt the natural ecological cycling of material. When pollutants enter ecosystems, they further diminish the health and prosperity of raw-material production (Boons 2013). If the environment cannot handle the levels of contamination, it is at risk of irreparable degradation leading to a complete loss in a raw-material source (Meadows et al. 2005). Beyond impacting general environmental and social prosperity, it increases the complexity a producer faces in sourcing raw materials. Though globally there has been attention drawn towards analyzing the efficiency of waste streams, the vast number of materials being moved through economies is done without optimization of their potential value. Innovation through the transition of waste streams to value streams presents a viable solution (Meadows et al. 2013) but transitioning waste streams to value streams requires an innovative approach. Boon (2002) describes three of the main barriers in building ecologically inspired systems:

1. Technical impossibilities
2. Gaps in knowledge about the ecological impacts of productions
3. The challenges in integrating the cooperation of autonomous actors involved in systems development.

Specifically in transitioning waste streams to value streams, Romero-Hernandez and Romero (2018) identify the three main hurdles in closing the waste to resource loop:

1. Lack of clear starting point
2. Lack of innovative ideas
3. Lack of top-down leadership.

Across waste stream types there is a lack of infrastructure available to manage closed loop cycling of resources (Betram et al. 2002). Developing a systems-based framework to address common barriers is needed to accelerate the shift to circular design within any production process. To approach this transition, an understanding of the potential of circular economies and waste streams as value streams is needed.

CLOSING THE WASTE AND RESOURCE LOOP

The Future is Circular

When waste is properly managed, and its value optimized, the health of the environment is cultivated. This leads to increased economic efficiency and quality of life (Meadows et al. 2005, Boons 2013, Bocken et al. 2019). By creating a circular system, the cycling of resources through a system reduces the need for raw material inputs and increases revenue potential (Genovese et al. 2017, Bocken et al. 2019). Sustainable design innovates the effectiveness of production systems and cuts down production costs (Boons et al. 2019, Bocken et al. 2018). Production and sale cycling times are lowered by eliminating the raw-material harvest and refining stages (Bocken et al. 2019). Through reintegrating waste streams to value streams, the cost of the product is also reduced (Romero-Hernandez and Romero 2018).

A circular system is more resilient. When waste is moved through production systems designed for closed cycling, the design mimics the movements of resources through natural systems (Meadows et al. 2005, Gamage and Hyde 2012). Like in an ecosystem, a circularly designed system defines no by-product as waste. Rather as resources ready to be recycled, reformed, and put through the system again. When waste streams become value streams, the system becomes self-sufficient causing a cascade of resiliency-based benefits. By implementing a circular design, industrial symbiosis is achieved. This is when waste materials from one process become the raw material for another, or the by-product from one industry can be repurposed into the production of a different industry (Bocken et al. 2019). Through the development of integrated system design, innovation, and economic expansion does not need to be limited when energy-use is sourced sustainably, and when waste is redefined as a resource (Gamage and Hyde 2012).

Copper in Medical Device Wiring

Globally copper is used at a rate of 26.7 million tons per year (International Copper Association 2021). As a key material in the construction of electronics, copper is a high-demand resource in the modern technological economy (Northey et al. 2014). As a main component in electronics, copper is vital for the transition of the global infrastructure to sustainable technologies such as electric vehicles and solar panels. Though copper has high value, it is being lost through poorly designed waste management (Bertram et al. 2002). While 95% of copper has the potential to be recycled, only around 40% of global copper is recaptured before entering landfill where it becomes inaccessible (Wang et al. 2021). Around 48% of copper is lost to waste streams in Europe (Bertram et al, 2003, Soulier et al. 2018), and a staggering 67% of copper is lost to waste streams in the United States (Wang 2021).

Copper is mined primarily in South America and then sent to refineries primarily in China to be processed for use in manufacturing (Kapur et al. 2006). The environments where copper is mined are highly impacted by extraction. Mining destroys the physical environment and releases pollutants causing extensive ecosystem damage. After their prescribed use, products containing copper are either disposed of in landfill or incinerated causing harmful levels of pollutants to enter the environment and degrade ecosystem functionality further (Reijnders 2003).

While high-quality copper ore is the goal of extraction, as reserves decrease mining will be forced to focus on lower-quality ore requiring extensive refinement before it can be used. This requires mines to expand causing increased environmental damage surrounding extraction sites. These factors will cause the cost of copper to increase, imposing strain on copper dependent industries (Northey et al. 2014).

By developing circular systems for the copper industry, the resiliency of copper-based economies increases. Fortunately, copper can be recycled indefinitely without losing its quality. Newly mined copper and copper recovered from waste streams have no quality difference. With the demand for copper increasing but exploration not yielding adequate new sources, there is a substantial reserve we have yet to optimize (Kapur et al. 2006). The copper currently circulating the economy has the potential to fill the need-gap of future copper (Copper Alliance 2021). Current reserves are projected to be sufficient for the next twenty years, but beyond this there is uncertainty about the availability of new sources (Northey et al/ 2014). An ideal material to be used in a circularly designed production cycle, copper waste streams can easily be transitioned to value streams (International Copper Association 2021).

With the future of copper reserves uncertain, companies need to expand their scope of viable sources to avoid the costs associated with limited supply. By developing infrastructure to transition copper waste streams to value streams copper is kept in the economy. This eliminates the need for mining raw-material and lowers the impact copper waste has on the environment when poorly managed. Restored ecosystems cause a spill-over of social and economic benefits associated with higher quality and abundant environmental reserves (Reijnders 2003). Companies implementing circular copper production cycles lower their costs, increase their revenue, and shorten

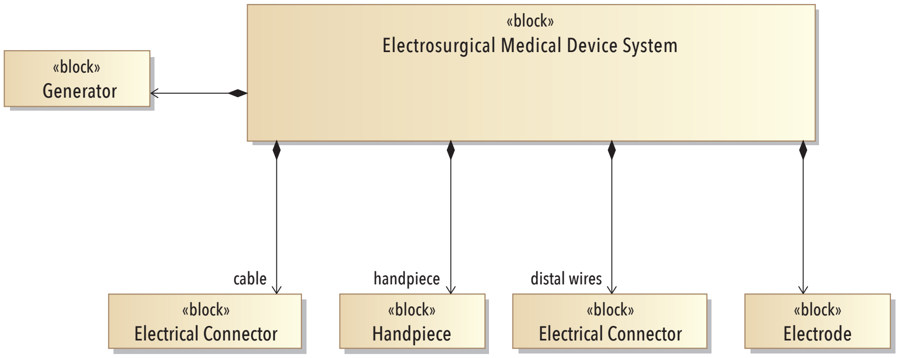

Figure 4. Typical composition of an electrosurgical medical device system

manufacturing times (Romero-Hernandez and Romero 2018).

Case Study. The following discussion focuses on a case study from the medical device industry. In this case study, we analyzed copper use in an electrosurgical system, which is commonly used in surgical procedures. Specifically, we focused on the largest market, bipolar vessel sealing devices, as they are commonly used in laparotomy and laparoscopic surgical procedures (Massarweh 2006). Figure 4 shows the components which comprise this system. The handpiece, electrode and distal wires are attached to the generator via a cable, composed of braided and sheathed copper wires. Of the components shown, only the generator is designed explicitly for reuse. By design, the handpiece, electrode(s) and electrical connectors are meant to be discarded after a single-patient use.

In 2022, it is estimated that over 4.8 million single-use disposable electrosurgical devices will be used (Grandview Research). Most electrosurgical devices are discarded as biohazard, which introduces a large amount of reusable copper into biohazardous waste. Over 40 tons of copper from cable connectors will be incinerated or interred in landfills in 2022 (EPA 2022). The anticipated market increase for electrosurgical devices is 5.73% through 2030 (Strategic Market Research 2021), at which point surgical cable connectors containing a cumulative 500 tons of copper will be discarded.

Although the quantity of copper used in electrosurgical devices is a fraction of a percent of the total global copper consumption per year, there are significant cost implications of discarding copper in surgical devices. As the copper reserves decrease, the price of copper is expected to increase. The average price of copper from 2019 to 2021 was $6500 (USD) per ton (Macrotrends) and bipolar medical device manufacturers spent less than $300,000 (USD) to support the production of the 4.8 million devices used in 2022. Goldman Sachs anticipates the price of copper will increase to $15,000 (USD) per ton by 2025, which is a CAPR of 39.7% (Bloomberg 2022). By 2025, the medical device industry should expect to spend over $900,000 USD to support the market demand; more than triple the spend from last year. By 2030, this price could be over $6.5 million USD.

Medical device manufacturers can decrease raw material cost by considering reuse, repurposing, or recycling of surgical cable connectors. This not only saves signif-

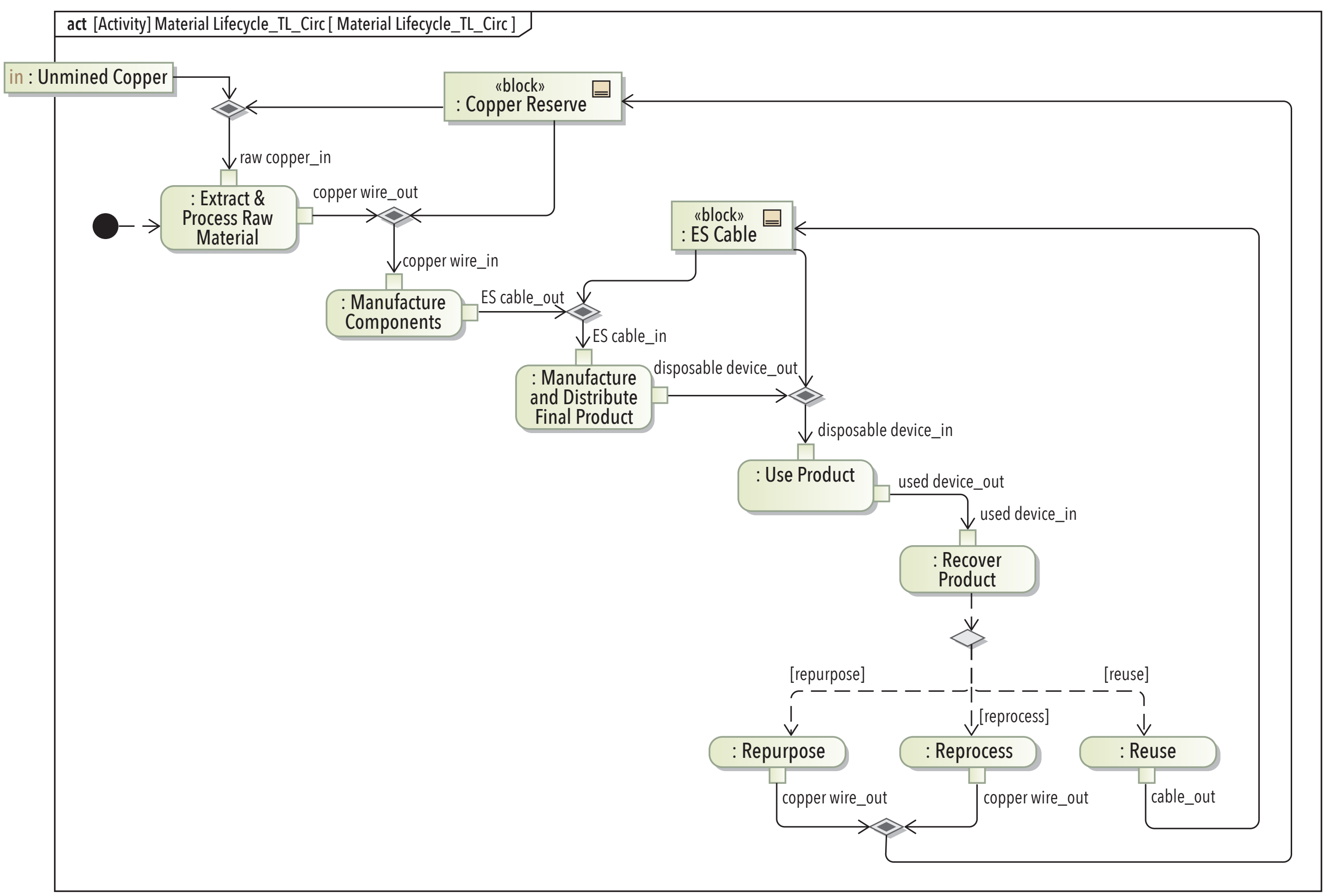

Figure 5. Illustration of the possible circular pathways in medical device manufacturing

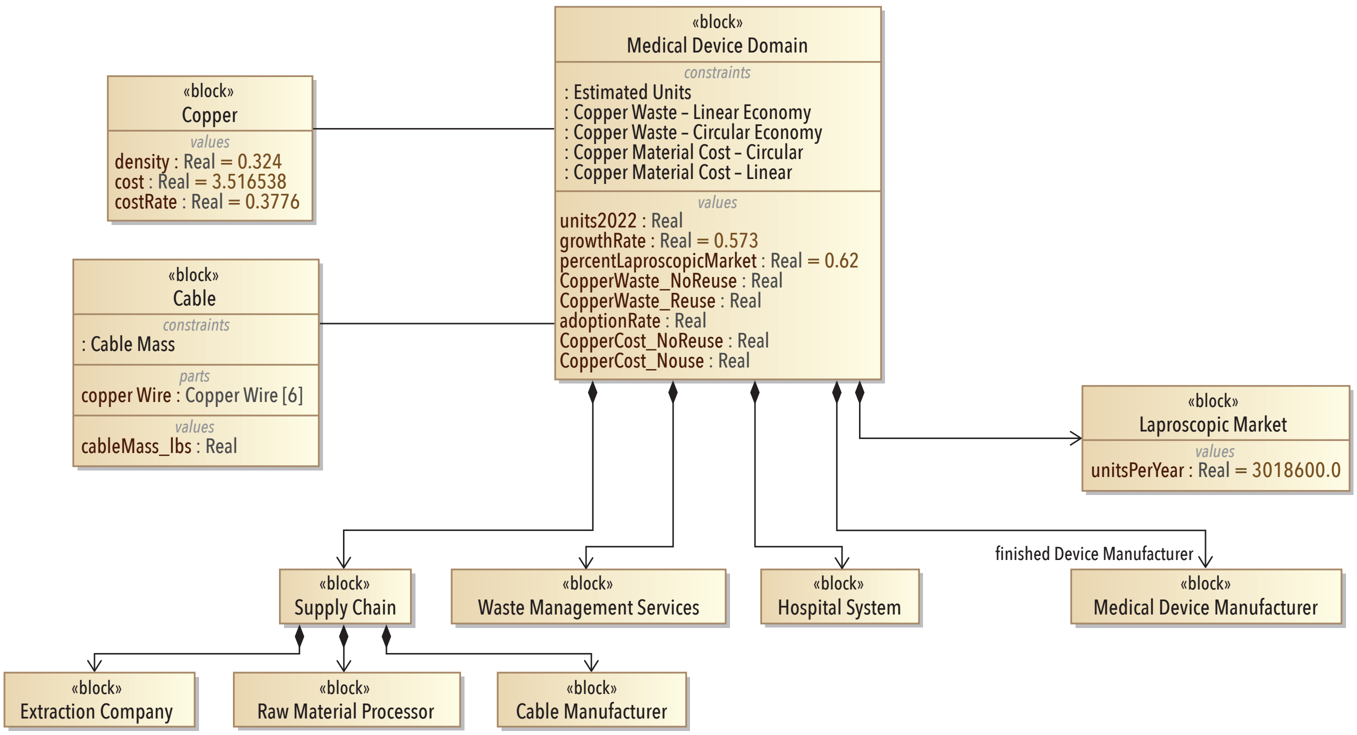

Figure 6. Definition of domain of electro-surgical systems

icant cost to the device manufacturer and preserves their supply chain, but also aids in preserving the copper reserves which in turn will combat the global price of copper. Figure 5 illustrates the flow of copper throughout the lifecycle of an electrosurgical (ES) device as it may be imagined using circular design principles.

Three options are shown to demonstrate how the copper wiring of the ES cable can be maintained at varying levels of material value. Reuse refers to maintaining the ES cable in its whole form and being re-sterilized by either the original device manufacturer or the hospital central processing. Repurpose refers to harvesting the copper wires and reutilizing them in wire form. Reprocessing refers to complete recycling and use of raw copper in a new form. This is in contrast with the current linear system, in which the entire medical device is used once, and the copper is discarded as waste.

The analysis of the effects of copper reuse was prepared using SysML parametric analyses based on the definition of the medical device domain in the context of electrosurgical systems shown in Figure 6.

The analysis was completed using the parametric diagram shown in Figure 7. This parametric analysis considers both the case where copper is reused and the case where it is discarded.

Figure 8 displays the anticipated copper consumption for electrosurgical devices over the next 50 years and the total price medical devices manufacturers should expect to spend on copper each year to support the manufacturing of surgical cable connectors given no reuse of cable connec-

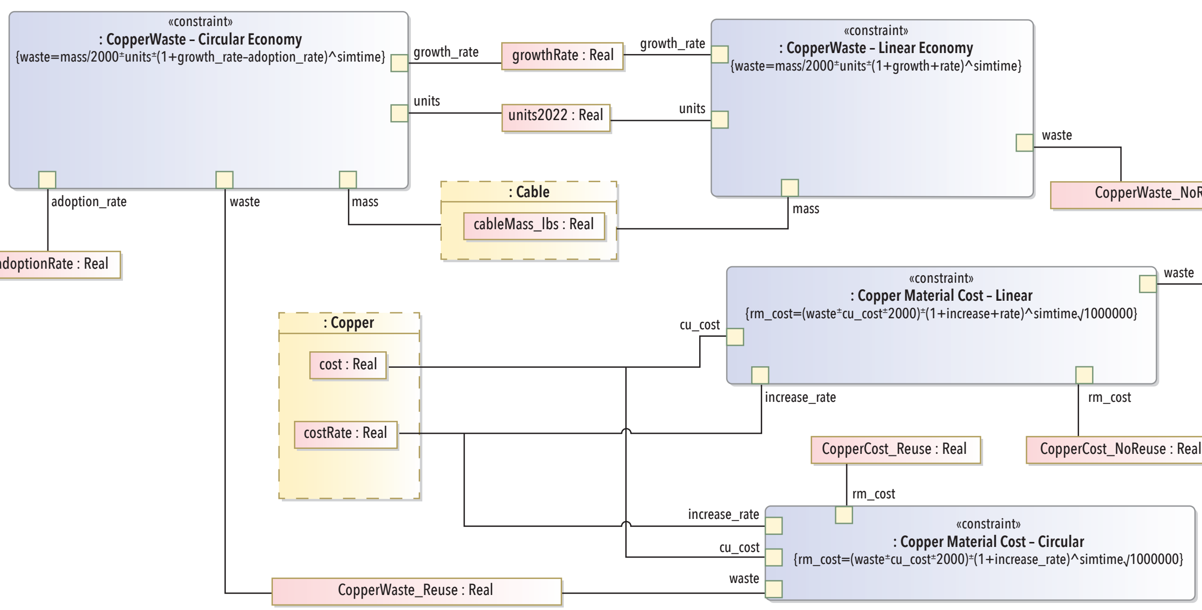

Figure 7. Top-level parametric analysis comparing circular to linear economies for copper use in electro-surgical devices

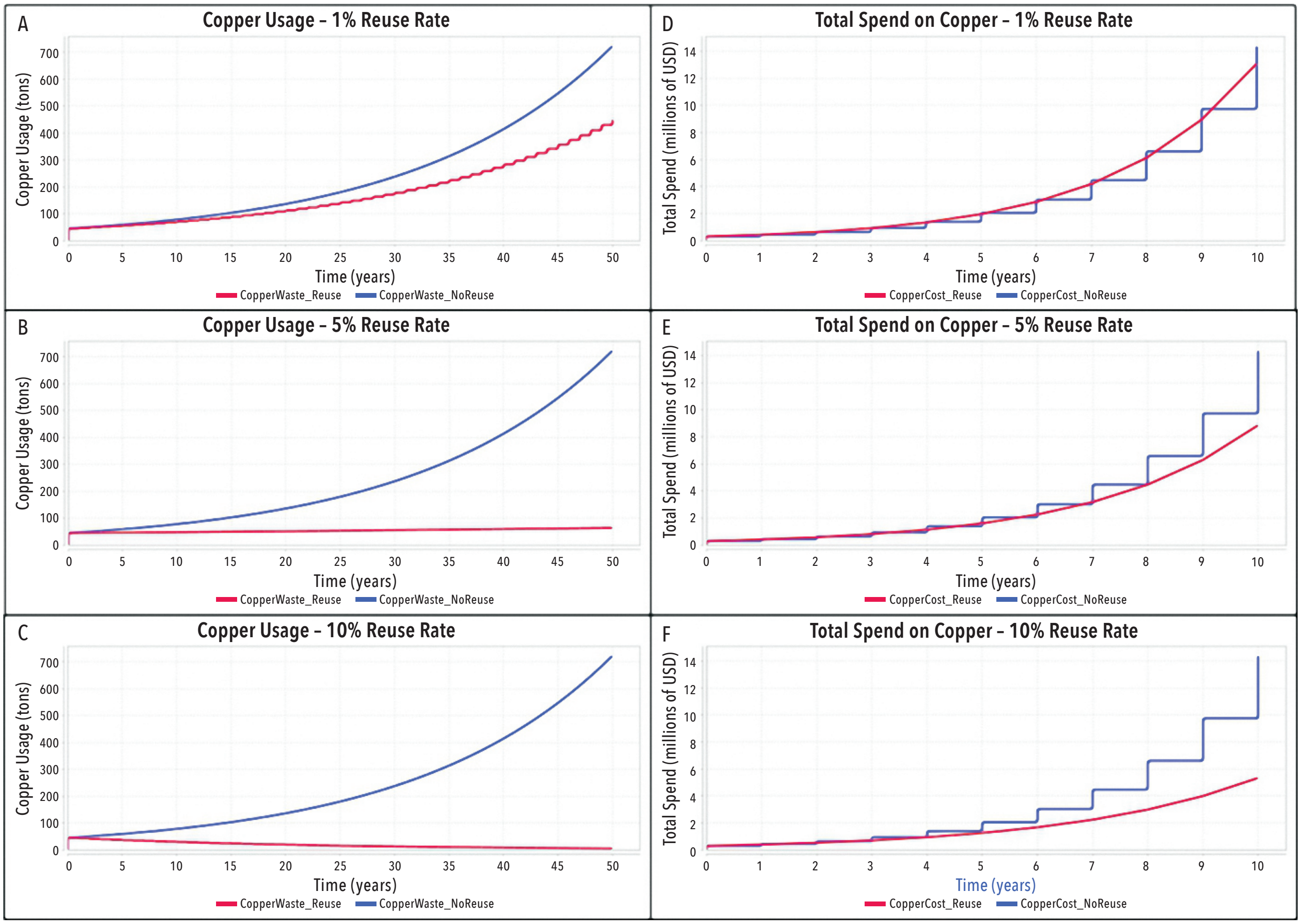

Figure 8. Anticipated copper usage from global copper reserve for electrosurgical devices over the next 50 years and the total price medical devices manufacturers should expect to spend on copper each year; A, B, C – Copper usage from reserve with 1%, 5%, and 10% annually increasing reuse rates; D, E, F – Total spend on raw material copper supply with 1%, 5%, and 10% annual increasing reuse rates

tors. Figure 8 also displays the anticipated copper consumption and expenditure if manufacturers increased the reuse of cable connectors 1%, 5%, and 10% annually. This analysis assumes that the typical electrosurgical cable is ten feet long and comprises six strands of 30-gauge copper wire.

Figure 8A, 8B, and 8C portray the anticipated use of copper from the global copper reserve given annual reuse rates of 1%, 5%, and 10%. In 50 years, medical device manufacturers could decrease the anticipated copper consumption by a third by increasing the reuse of cable connectors by 1% each year. Manufacturers could maintain the current consumption of copper by increasing their reuse rate by 5%. If device manufacturers increased their reuse rate by 10%, they could presumably decrease their consumption of copper. This effort would reduce the strain on the global copper reserve in addition to decreasing the environmental byproducts of medical waste incineration.

To support the electrosurgical market demand in 2030, medical device manufacturers will need to produce a total of 8.5 million surgical cable connectors consuming 70 tons of copper. Without introducing recycling, repurposing, or reuse of cable connectors, 70 tons of copper will be discarded at the point of use and $6.6 million USD will be incinerated alongside other biohazardous waste. Figure 8A, Figure 8B, and Figure 8C show that if medical device manufacturers increased their annual reuse rate by 1%, 5%, and 10%, respectively, the raw copper supply from the copper reserve would drop to 65, 47, and 31 tons. Figure 8D, Figure 8E, and Figure 8F show that the price device manufacturers should expect to spend on copper would drop from $6.5 million USD to $6.1 million USD, $4.5 million USD, or $3 million USD, respectively.

Integrating Value Streams

While collaboration across sectors is possible, internal repurposing pathways from waste to new production material is the most efficient pathway in closing the waste to value stream gap (Boons 2002).

In-order to build a sustainable model, three focus points must be addressed during the experimentation phase of the system as outlined by Bocken et al. (2019):

1. Construct clarity: the issue is a lack of defined contextualization in the development and testing of sustainable models
2. Boundary setting: without a defined boundary, a system will not be easily evaluated, and its functionality cannot be accurately represented
3. Uncertainty in outcomes: it cannot be guaranteed that a change in the model will result in a more sustainable functioning.

Systems engineering provides several tools and techniques that, when properly applied and considered, are useful in both characterizing current state of process and identifying evolutions of current state to achieve the necessary future state of sustainable and circular development. The following four considerations identified by

Boons (2013) are transferable to systems engineering practice.

1. Causal complexity. This is a familiar concept to systems engineers. The characterization of the impact of interactions among and between systems and their interfaces is a foundational concept in systems engineering.
2. Adaptability. Translated to systems engineering vernacular, adaptability refers to the resilience of engineered systems, production mechanisms, supply chains to consider future states and plan for the inclusion of circular design.
3. Inclusive system boundaries. By recognizing environments and environmental factors as stakeholders of our system, we expand our scope of practice to ensure our design decisions properly capitalize on opportunities to include elements of circularity.
4. Selection pressure. By actively considering environmental factors, systems engineers can apply pressure to vendors and suppliers to source materials and components from increasingly circular sources. This work begins with appropriately inclusive requirements.

FINAL THOUGHTS

Romero-Hernandez and Romero (2018) propose eliminating waste streams through efficient production design. The following points, if addressed by systems engineers, may contribute to a reduction in overall waste by aiding in the conversion from linear design to circular design, thereby converting existing and future waste streams into value streams.

1. Identify environments as stakeholders in early stakeholder identification and research.
2. Expand system scope and boundary analyses to ensure interfaces with sources and sinks are considered.
3. Explicitly identify raw material suppliers and waste handlers as stakeholders.

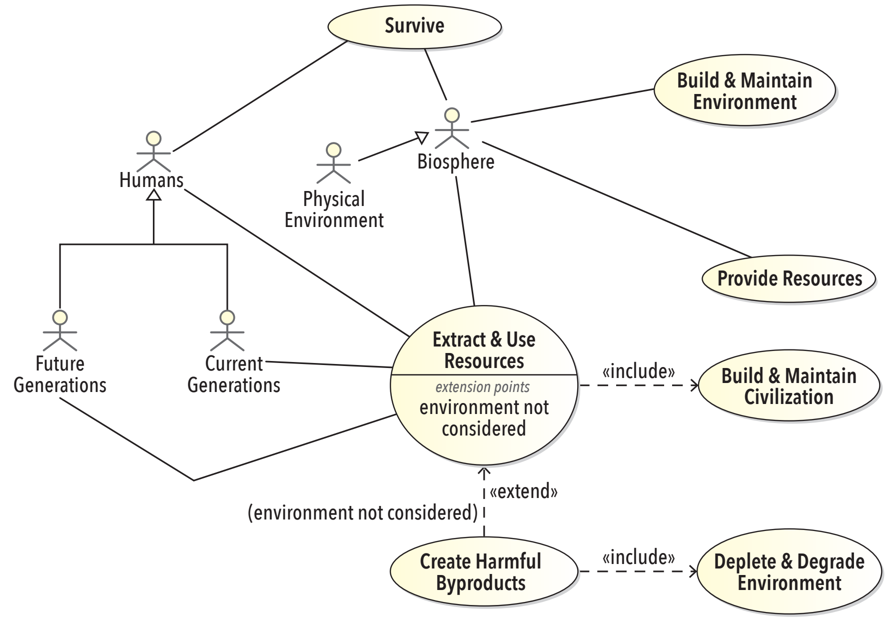

Figure 9. Use cases and stakeholders in association to resource extraction and use

4. Using the newly identified stakeholders listed above, ensure those stakeholders' needs are correctly and adequately transformed into system requirements.
5. Include environmental considerations in material and production process selection trade studies.
6. Include sources and sinks as references in manufacturing models such that interfaces can be described and the impacts of material selections and production methods on environmental interfaces can be assessed.

Global environmental conditions are shifting, and resilience in planetary systems is needed to meet the future. With a range of stakeholders from the environment to future generations, the flow between human-made systems and ecological ones becomes a point of transformation. By increasing system efficiency and valuing all by-products as resources the global economy can accelerate the evolution of human-designed systems (Boons et al. 2013). Closing the gap between waste streams and value streams is vital in meeting economic material demands (Bocken et al. 2019). In the pursuit of resilience, companies shifting to circular models for copper and other all resources have the opportunity to contribute to both internal and planetary prosperity.

By taking the steps outlined above to begin moving toward a circular production design, we divert the waste stream pathway to create positive economic impact instead of environmental damage. As shown in Figure 9, resource use and disposal can be reimagined to reinforce ecological and economic prosperity, both now and for future generations. By limiting harmful byproducts and utilizing circular design, the environment is maintained alongside civilization.

The field of circular economic design needs continued innovation. Drawing inspiration from the wasteless design of ecosystems is an ideal place to start in the integration of economy and environment (Gamage and Hyde 2015). Shifting the definition of waste streams to value streams presents an opportunity to evolve the economy to meet the environmental, and therefore human, needs of the future. ■

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Casey Medina leads Studio SE as the president and CEO. Under his leadership, Studio SE provides a range of exemplary professional development courses including model-based systems engineering. He has practiced systems and quality engineering across industries including medical device, aerospace, defense, and transportation industries. His expertise extends across disciplines including system development, requirements engineering, model-based systems engineering (MBSE), human factors, quality engineering, risk management, and medical device design control. Professionally, he is focused on developing the art of systems engineering in a manner that fosters adoption and acceptance by organizations resistant to change. He applies systems engineering practices and principles to enable rapid system development and is working to enhance the use of MBSE as an enabler for usability and human factors analyses. He has deployed MBSE to analyze social systems and homelessness. Casey and his team at Studio SE are pioneering the use of MBSE to evaluate natural systems and deploy MBSE to manage and solve sustainability issues.

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