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Cross-Domain Comparison of Design Factors in System Design and Analysis of Space and Transportation Systems

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Abstract

Transportation, an infrastructure-focused domain, and Space, a less infrastructure-focused domain, are compared according to five design factors: mission objective(s), stakeholders, concepts, constraints, and dynamic lifecycle issues. The comparison uncovers domain-inherent biases in decision and design methods originating in both domains. Causes for domain biases and implications for a domain-independent decision and design method are discussed. The goal of this research is to make system designers more sensitive to domain-inherent biases and thus help facilitate communication and knowledge-sharing across domains. Facing changing contexts and value perceptions, system designers increasingly face seemingly new issues and can learn from other domains where these issues have already been addressed.

Introduction

Infrastructure such as transportation or energy provides the physical framework for people to satisfy their needs on a daily basis. Experts in industry and academia possess great expertise in the design of infrastructure system components such as vehicles or network flow optimization. However, experts in the systems engineering community point out a lack of understanding of their socio-technical, political, environmental, and economic context. Rigorous methods for designing and evolving future infrastructure systems are needed (Hansman et al. 2006). Systems Engineering, which enables the successful realization of large, complex systems, needs sophisticated decision analysis under conditions of high uncertainty, and a holistic design process in order to take into account changing system contexts and value expectations. Comparative analysis of domains is an important step in order to gain insight into fundamental and domain-specific issues in engineering systems, and to develop these sophisticated decision and design methods. In this paper, an infrastructure-focused domain is compared to a less infrastructure-focused domain, namely transportation to space. Space systems define all of the devices and organizations that form a space network, including spacecraft, mission payloads, ground stations, data links among spacecraft, mission or user terminals, launch systems; and directly related supporting infrastructure (The free online dictionary 2008). Transportation systems consist of physical objects, typically vehicles, the network infrastructure and equipment, and operation schedules that move passengers or goods (Wordnet 2008). Space and transportation systems are compared along five dimensions that were inspired by Multi-Attribute Tradespace Exploration, a decision and design method developed using space applications, but with the intent to be domain-independent (Ross 2003, Ross 2006b).

Motivation

The motivation for this paper is three-fold. First, as system designers increasingly face changing contexts and value perceptions, they will face new issues and problems. By comparing domains and uncovering biases, this research helps system designers to anticipate and think through issues that are not addressed in their specific domain. A bias is an inclination towards something; a predisposition, prejudice, preference, predilection (Wiktionary 2008). The knowledge of domain-inherent biases reduces the likelihood that system designers will be surprised by new issues or problems arising from unexpected factors.

Second, knowledge about common issues in other domains and sensitivity to domain-inherent biases will help facilitate communication and knowledge-sharing across domains. As changes occur in the context and value expectations in a specific domain, it will be useful to learn from other domains in which one's own new issues have already been addressed. With systems professionals increasingly finding themselves working in multiple domains in their careers, there is a need to understand the similarities and differences in design factors as related to different domains.

Third, Systems Engineering is based on the hypothesis that large, complex systems will encounter a universal set of issues. Common issues and domain biases in specific domains point out requirements for the development of domain-independent decision and design methods. These methods are the subject of ongoing research.

Important commonalities between space and transportation systems suggest that comparative research leads to useful insights for both domains. These commonalitites include their high price tags, their use as public policy levers, the existence of secondary, typically non-technical objectives (Larson and Wertz 1992, Sussman 2000), and an often long development phase.

The paper is organized in five areas of comparison: The five subsections are the definition of mission objectives, stakeholders, system concepts, constraints, and dynamic lifecycle issues. Tables 1 to 5 summarize the findings for each of the five sections. A final conclusion summarizes implications for cross-domain decision and design methods.

Five Areas for Comparison

Mission Objective(s)

Differing roles for mission objectives. The mission objective is a concise summary of the broad goals the system should achieve in operation and is derived from the essential needs that drive development of the system. Primary space mission objectives include communications, navigation, weather surveillance, scientific observations, and space exploration. (Larson and Wertz 1992) The explicit incorporation of a mission objective in the design process goes back to the fact that typically a single institution (DoD, NASA, ESA, military) is in charge of capturing user needs and of formulating a mission statement. Nearly all space missions also have a hidden agenda of secondary, typically political, social, or cultural objectives. In transportation systems, a clear mission objective does not typically precede the formulation of these goals. (Sinha and

Labi 2007) propose a pyramid of desired outcomes for a transportation project with three *overall goals* at the top that are meant to broadly describe "what the transportation action is meant to achieve" (Sinha and Labi 2007, p. 21). The three goals are efficiency (is the output worth the input?), effectiveness (is the action producing the desired outcomes?), and equity (are diverse segments of the population receiving their fair share of the action's benefits?). While desirable in every system, these overall goals are different from a mission objective in that they do not explain the purpose of the transportation project, the captured need that the project is intended to fulfill. There are three possible reasons why defining a mission objective did not evolve as an integral step in the transportation system planning process in the same way it did for space systems.

Table 1: Comparison of "Mission Objective(s)"

Mission factors	Space	Transportation
Defined Mission Objective	Integral part of design process	Typically not made explicit
Equity	Typically not considered	Essential to consider

Possible Reasons for less emphasis on mission objective in transportation planning process

1. **Multiplicity of interests.** The more specialized the capability of a system, the smaller the number of people interested in it. Transportation systems serve a broad range of interest groups through all parts of society and the economy. Unlike space systems, they could have very noticeable negative impacts for large parts of the population, which are discussed in the next section. The number of stakeholders and stakeholder groups is typically greater in transportation than in space, and their interests more varied and controversial. Goals and objectives in transportation systems are generally developed through extensive examination of top-level agency requirements, by soliciting the perspectives of users and other stakeholders and by outreach to the general public (Sinha and Labi 2007). The mission objective in transportation systems therefore tends to be more difficult to define and to justify than in space systems.
2. **Mission objectives can be a sensitive matter.** Since transportation investments are a prime public policy lever, the mission objective can be unarticulated, sensitive, or even not consciously known by decision makers. Infrastructure investments such as airports are used as measures to boost employment and economic development in a certain area both through the construction work itself and the expected benefits from the transportation system. The mission objectives can be highly sensitive in a political environment and it may be intentionally left not explicit. (CNN Politics 2008)
3. **Enabling nature of transportation hides mission objective.** Infrastructure, by definition, is the "resources (as personnel, buildings, or equipment) required for an activity" (Merriam Webster Online Dictionary 2008), which underlines the enabling character of systems such as transportation, communication, energy, and other infrastructures. Often some mission objectives are implicit in transportation system concepts, which is not true to the same degree for space sytems. For example, implicit in the concept of train is the movement of people and freight between two points along the rail. No such expectations exist for space systems.

Differing importance of Equity. While a classical problem for transportation is the crossing of territory of an uninvolved party, and the subsequent issue of fairness, this type of problem does not usually arise for space systems. Typically decision and design methods originating in the space domain do not make judgments about the issue of fairness or distribution of benefits and the implicit weighting of relative importance of stakeholders. Space mission methods require the definition of mission objective(s) as input, and help to make better decisions for fulfilling those explicitly defined objectives. The problem is to evaluate the impact of externalities and to ensure a balanced realization.

Stakeholders

Explicit consideration of 'losers', forced stakeholders, and stakeholders without decision making power. Over 30 definitions of the term 'stakeholder' demonstrate that the concept is hard to define in its entirety (Mitchell et al. 1997). In transportation planning, three types of disadvantaged stakeholders are important that are not typically considered for space systems. *'Losers'* are stakeholders that are affected by an enterprise's externalities, but do not receive any value from the enterprise's activities, such as residents who live close to airports but who do not fly. Externalities include noise, pollution, increased risks for accidents, visual impairment, and forced relocation. For an extensive discussion of externalitites see (Sinha and Labi 2007). *Forced stakeholders* do not choose to have a stake in the system, but are forced by the decisions of others, such as adjacent communities to transportation facilities. *Stakeholders without decision making power* can be either without formal or without any decision making power. Informal decision making power is exerted through lawsuits, public protests, boycotts, and media campaigns, to lobby decision makers. The effect of these actions is typically unclear. Examples for these disruptive actions are the numerous lawsuits in airport design that typically delay the planning process for years. For space systems, stakeholders participate in a system because, in their judgment, their benefits outweigh their costs. Stakeholders without formal decision making are typically not considered. 'Lean Enterprise Value', a book based on research in the aerospace industry, provides a definition of a stakeholder, which does not account for stakeholders who are affected by externalities and do not receive any value from the enterprise's activities (Murman et al 2002). The definition may also be a result of a tendency for space system methods to neglect externalities, since they often do not play a significant role. This paper follows the Lean Enterprise Value stakeholder definition if extended to account for the three disadvantaged stakeholder types.

Number and diversity of stakeholders in transportation. Typical stakeholders in space systems include the government, the science community (both academia and government), the aerospace industry, and sometimes commercial customers or international partners. For transportation systems, typical stakeholders include the government at all levels, customers (individuals and businesses), private investors, vehicle and system operators, adjacent communities to facilities, enterprises that operate or manufacture vehicles, and NGOs. The environment, society, and the media are stakeholders in both systems, however with different degrees of interest. It was argued in the previous section that the less specialized capabilities of a transportation system result in a greater 'market size', the market here denoting all people with an interest in the system. This interest can be based on its capabilities, externalities, economic, or other impact. For space, the stakeholder set is narrower, since except for a select set of experts, most people are not affected by the quality of the design of space missions in their day-to-day lives.

Negotiation and preference aggregation harder with more stakeholder groups. The larger number of stakeholders in transportation makes negotiation and aggregation of preferences more difficult. (Arrow 1963) shows that there is no theoretically ‘good’ way to aggregate the preferences of a group, so that an imperfect aggregation mode needs to be chosen. Practical problems include the choice of an expert representative of a group, for example for multiple government agencies, and preference assessment of large population groups through polls. These common practices exhibit difficulties in representativeness and impartiality.

Stakeholder determination and salience decision problem in transportation. Since there are typically more stakeholders with formal or informal decision making power than can be treated in an analytic decision and design method, the most important stakeholders need to be identified (stakeholder salience problem). Since stakeholder identification and salience is not supported by clear-cut guidance and best practices (Rebentisch et al. 2005), experience, intuition and knowledge play an important role. Experience shows that if even small and seemingly insignificant stakeholders have the power to severely impact a system’s design process or its operations, then their needs should be considered in the system’s design. (Sussman and Mostashari 2005) propose a specific categorization for transportation stakeholders, which helps to identify stakeholders for different transportation contexts: influence/power, stake, and knowledge. They distinguish stakeholders with economic/political influence (high stake, medium to high power and differing levels of knowledge, knowledge-producers (low stake, low power, high knowledge), and other affected stakeholders (high stake, low power, differing levels of knowledge), and extensively enumerate examples. The ability of ‘losers’ to disrupt a system shows that a transportation system’s performance depends on a basic confidence of all important stakeholders with the system, including those with no formal power.

Table 2: Comparison of “Stakeholders”

Stakeholder factors	Space	Transportation
Forced stakeholders	Not addressed	Addressed
Stakeholder groups with important informal power	Not addressed	Addressed (informal power through destructive actions)
‘Losers’ (only risk, no value)	Existing, but downplayed	Addressed
‘Market size’	Limited to experts	Very large

System Concepts

Understanding of ‘system concept’. A concept is the mapping of function to form (Ross 2003). While operations are important in space systems, the emphasis tends to be on vehicle design (Larson and Wertz 1992). Concepts for space systems include swarms of satellites, single monolithic spacecraft, fractionated spacecraft, ballistic spacecraft, and satellite constellations, among others. It appears from (Taylor 2007) and (Sussman 2000) that the emphasis is on the dual aspects of operations and vehicle design in transportation systems. System concepts for transportation can be as broad as the general choice of a transportation mode among air, rail, road, and waterway, or as narrow as a schedule change within an already existing system, depending on the (explicit or tacit) mission objective. If the mission objective is to provide access to an airport, system concepts include bus, rail, commuter rail systems, and individual transport by cars. Trains are typically only efficient if the rail infrastructure already exists, otherwise, bus service offers several advantages including less cost, more flexible routing, and easy exchange of vehicles for maintenance and repair.

Inheritance. Transportation systems are almost never designed from scratch. The designer will often be constrained by previously developed vehicles and infrastructure. An *inheritance* is the physical object or conceptual or behavioral artifact that is received from a former system. From a holistic socio-technical perspective of the system, inheritance includes not only physical objects, but also the embedding context in which the transportation system operates. Examples of 'soft inheritance' include interaction with other transportation systems, and end users' expectations of certain levels of service, connections, and pricing structures. Inheritance can function as a constraint, but differs from true constraints in that it often sets a baseline, and can be altered for a price. As an example, existing trains can be replaced, and schedules can be changed, but the disposal costs for old trains and the passengers' need to rely on connections to other transportation systems may affect the performance of a concept with inherited components. While physical system and expectation inheritance does play a large role for space systems as well, this issue is not often discussed in the space system literature. According to the pedagogy of graduate space system design courses, clean sheet design has a strong appeal and often overrides discussions of "messy" inheritance.

Different control situations over system components. Concurrent design requires a designer to exercise control, the authority to change, over a system in order to impose his design choices on the components. For US space systems complete control or control at a level of dispersion that allows negotiation are a prerequisite for a spacecraft being built. In transportation systems, stakeholders' degree of control over transportation system subsystems varies tremendously. For space systems, NASA and the US Air Force often are single decision makers over the vehicles they own. For air transportation, two groups of actors make decisions about the system: airlines and airports. For space systems, occasionally multi-service satellites (e.g. Navy, Air Force, etc.) are under split control. For road traffic, government or private investors own roads, bridges, and tunnels and navigate traffic on them, whereas trucking companies and individuals own and operate the vehicles. Since the control of the roads and control of the vehicles reside in different stakeholders, concurrent design of a system encompassing both is difficult due to the dispersed decision making power, for instance for a trucking company operating on public roads.

Table 3: Comparison of "System concepts"

Concept factors	Space	Transportation
Understanding of concept	Mainly physical	Physical and operational
Inheritance	Not adressed, 'soft inheritance' plays important role	Common issue, addressed
Control over system	Dispersed or central, decision makers negotiate and co-design system	Central or dispersed at various degrees, co-design not always possible
Compensation for losers	Not an issue	Common issue, addressed
Types of cost	Monetary	Multiple types of cost (monetary, environmental, other)

Compensation as part of the design. Compensation for 'losers' for transportation systems is one way to achieve a redistribution of costs and benefits that is more desired by a decision maker, typically a government body. Unequal distribution of costs and benefits is a problem not unique to transportation systems, but unlike for space systems, it is treated in the transportation literature. The topic of redistribution of benefits is a controversial one since it requires an interpersonal comparison of utility (i.e., how much satisfaction of person A should be traded for how much satisfaction of person B, and on what basis are those levels of satisfaction compared?). In order to make a decision about a possible compensation, the level and distribution of compensation should to be considered as part of the system concept. This means that design needs to be expanded to include design factors that affect user preferences for a concept and the cost of a concept in the same way as other design variables, but are not naturally related to the actual system.

Different types of costs. The earlier discussion about externalities suggests that there are costs incurred and imposed by the system other than monetary costs. Space systems do produce externalities in the form of waste and debris in space, however, these effects have largely been secondary and are typically not an issue of concern during design. For transportation systems, environmental effects, and effects on quality of life often have very high priority to certain stakeholders (Schmidt 2005, van Eeten 2001).

Constraints

Constraints are unchangeable factors of any kind in the design process. Some constraints are obvious at the beginning of the design process, such as the laws of physics and legal constraints. It is important to have a broad view on the system to also consider less obvious constraints, such as human capabilities, to ensure the validity of the later analysis. Differences between space and transportation result from the embedded nature of transportation systems and the often geographically removed nature of space systems. An important issue confronting space systems is its need to operate in harsh environments, which has made design for robustness and survivability high prioritities. Unlike space systems, transportation is typically embedded in a market environment with its pressure to be profitable, even though a large number of transporation systems rely on governmental subsidies. The level of competition varies substantially, from very high (airlines) to very little for natural monopolies (some airports and commuter rail systems). All transportation systems are expected to meet the social norms of reliability and timeliness, which implicate the need to deal fast with disruptions.

Table 4: Comparison of "Exogenous factors"

Exogenous factors	Space	Transportation
Laws of physics, technological constraints	Yes (especially orbital dynamics, energy required to get there)	Yes
Maintenance	Yes, but downplayed	Important
Inherited infrastructure	Yes (mainly protection of national safety)	Yes (national safety an issue in border protection, but emphasis on personal safety of passengers)
Dual use (military-civil), and other restricted technology	Yes, adds a lot of regulations, restrictions on technology transfer	Plays minor role, mainly civil use
Safety	Difficult due to remotenss	Need for fastness and efficiency
Market structure	Low, but pressure to be	Very high to low, large pressure to

	resource-efficient increasing	be profitable/ resource -efficient
Social norms on performance	Survivability, robustness, no failure	Reliability, timeliness
Regulation	High	Regulations on international and all subsidiary levels, degree varying
Environmental constraints, land-use	Less important	Important
Impact of investment structure on design	Sunk costs of development, fixed launch costs	Discrete, bulky increase in capacity

As space system design moves more towards the development of an on-orbit infrastructure (Nilchiani and Hastings 2007, Long et al. 2007, Joppin and Hastings 2006, Richards 2004), these systems will begin to take on characteristics similar to those found for transportation systems including constraints, such as environmental externalities. Table 4 gives an overview over the context in which space and transportation systems are designed. Similar constraints, like the laws of physics, are very powerful since they suggest invariants in system design that need to be considered independent of domains.

Dynamic Lifecycle Issues

Definition of the end of system life. The lifecycles, meaning the useful lives, of transportation systems are highly variable. Systems that require high investments typically have a lifecycle of decades, such as trains, rails, roads, airports, and airplanes. What are commonly regarded as lifecycles for these systems are mainly approximations, for reasons of lack of data and controversy as to the end of a system's life. The end of a system's life is a question of definition, as it can be defined, for example, as the point of absolute failure, the failure to meet certain technical standards, or economic inefficiency due to too high maintenance costs (de Neufville 2007). In many cases the transportation system keeps running while components are being replaced. Road pavements are commonly regarded to have a lifecycle of 17-27 years, depending on the used material (de Neufville 2007). The transportation system that involves the roads however keeps functioning while single roads are being repaved, through narrowing of roads or redirection. In the automotive industry, 'lifecycle management' serves to satisfy the customer. New generations of luxury vehicles are released after a number of years that is well-researched by marketers. This point in time allows the customers of expensive cars to drive the latest model until the majority is ready for the purchase of a model of the next generation. Due to remoteness, inability to repair or upgrade, and high cost for development, space systems are typically built for 10-15 year lifetimes. The lifecycle of a system indicates how often systems are going to change. Even though the nature of change may be uncertain, the knowledge of when change is expected is vital for the development and evaluation of system concepts.

Changing contexts. Changing contexts impact user preferences and the perceived success of a system. Since the design and deployment of space and transportation systems is typically in the range of decades, these systems are likely to operate in multiple contexts. Recent examples for significant changes include rising priority of safety in air transportation after 9/11, and the emphasis on environmental efficiency in transportation in general. Another driver for change in transportation is the capability, cost and convenience of the communication infrastructure. Since communication can substitute for travel in some cases, increases in the attractiveness of this alternative can have a potentially strong impact on transportation. An example for a changing system context for space is the increased desire for a more infrastructure-like on-orbit architecture, which will confront space system designers with issues similar to those that infrastructure systems face today. As the political context of space system development has evolved from one dealing with a monolithic, well-funded adversary, to one with diffuse threats and rapidly changing technology, efficient use of scarce resources now plays an increasingly important role, which is equally similar to transportation. The new paradigm of operationally responsive space indicates a priority shift from classic (legacy) design to incorporate as many payloads as feasible to a new design of shortened schedules and hopefully lower budgets. While classic ('big space') design is performance driven, operationally responsive space is schedule driven. Operationally responsive spacecraft become desirable when a new capability is needed or there is a loss of legacy systems (Richards et al. 2008). Results of ongoing research in these areas may lead to useful insights for transportation systems.

Table 5: Comparison of "Dynamic Lifecycle Issues"

Lifecycle factors	Space	Transportation
Definition of the end of a system's life	Typically operational end of life, or end of mission	Varying, disposal problematic, system exists while components are being replaced
Lifecycle	10-15 years	Varying, in the range of decades
Changing contexts	Important	Important

Due to the long lifecycle and long design phase in both space and some transportation systems, the consideration of changing contexts and user preferences is crucial for sustained system performance for both domains. The need for changeable designs in space systems, and for a theory to help plan and implement infrastructure transformation, respectively, is pointed out by members of both communities (Ross 2006a, Hansman et al. 2006).

Discussion and Conclusion

Several common issues and domain-inherent biases of space and transportation systems are uncovered. The following summary lists incurred issues, which are discussed in this paper, and which are intended to help system designers think through issues that their system may encounter during its operation. This research is further intended to encourage system designers to share knowledge across domains. Ultimately, enhanced knowledge of domain-biases will help the systems engineering community to understand systems behavior and develop theories and methods that apply to systems independent of their domains.

Along with the 'classic' stakeholder who chooses a stake in a system because his benefits outweigh his costs, there are three roles of *disadvantaged stakeholders*: 'losers', that is stakeholders who bear costs but no benefits, forced stakeholders, and stakeholders without formal or even informal decision making power. Failure to account for these stakeholder groups can adversely affect the system if these groups make their dissatisfaction known through disruptive actions such as lawsuits or media campaigns. *Inheritance*, both in terms of physical components and social artifacts, is a reality in the context in which space and transportation systems are designed. *Dispersed control* over system components may limit the deployment of optimal design. Systems incur *multiple types of cost* which should be represented to reflect environmental and other non-monetary concerns. Similar to preferences, the aggregation of different cost types implies a value proposition by the designer.

Important decisions in the design of a system require not only technical, but also an ethical judgment by the designer. These questions include the consideration of the interests of powerless stakeholders, the compensation of these stakeholders, and the consideration of different types of cost. Knowledge-sharing between engineering domains in which this responsibility is addressed, such as transportation, and domains where this is not addressed, such as space systems, is highly desirable. Further comparative research between domains should test and complete the listing of issues that are pointed out in this paper, as well as refine decision and design methods. In particular, future research should demonstrate, through example, the effect of including stakeholders with informal or little power in decision and design analysis methods, the consideration of inheritance, and the accounting for multiple cost types. Ultimately, the aggregation of the views of individual disciplines will shape a more comprehensive view on the nature of complex engineering systems.

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