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An Axiomatic Design Approach to Reconfigurable Transportation Systems Planning and Operations

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Abstract: Transportation systems represent a critical infrastructure upon which communities’ and nations’ economic and social development depends. As infrastructure systems, they must be planned and operated to efficiently and safely move both people and goods. The needs of passengers and freight are uncertain and continually changing, which represent not only changes in system behavior, but also changes in system architecture. Such changes occur in the planning time scale when the system is intentionally modified, but also in the operational time scale when sudden and oftentimes unexpected changes occur (i.e. a bus or train breakdown). Addressing these changes requires a systematic representation of the evolution of the system architecture. This paper expands on recent work in which a theory of degrees of freedom in manufacturing systems was developed with the use of Axiomatic Design. The theory is specialized to reconfigurable transportation systems, which meet the Axiomatic Design definition of large flexible systems. The methodology is then applied on a small subsection of the Mexico City public transportation network to demonstrate its use in reconfigurability measurement and decision-making at the planning and operations time scales.

Keywords: Axiomatic Design, Reconfigurability, Reconfigurable Transportation Systems, Transportation Itineraries, Transportation Planning and Operations.

Introduction

Transportation systems represent a critical infrastructure upon which communities’ and nations’ economic and social development depends. In the 1990s, transportation systems the world over became increasingly strained by the continually evolving needs of a growing population that has trended towards concentrating in cities for the past 100 years (de Weck *et al.* 2011). Transportation systems pose particularly troublesome challenges for engineers due to their inherent nature as legacy systems, as well as the economic, political, and social factors that figure prominently in their decision-making – all of which makes them true engineering systems (de Weck *et al.* 2011). A key challenge is the need to find efficient ways to reallocate and/or adjust the capacity and capabilities of these systems to the places and times that need them most. These changes must be implemented quickly (a time scale of minutes) in order to minimize the disruption to supply lines and passenger traffic. Additionally, a transportation system’s resilience in the face of unplanned disturbances or events becomes an important quality factor. In order to achieve and support solutions for these issues, it becomes necessary to model the evolution of the system architecture. Reconfigurable transportation systems are proposed as a possible solution (Baca *et al.* 2013; Viswanath *et al.* 2013). They are defined formally as follows:

Definition 1. Reconfigurable Transportation System: A system designed at the outset for rapid changes in structure, in order to quickly adjust capacity and functionality in response to sudden changes in stakeholder requirements (Baca *et al.* 2013).

Reconfigurable transportation systems are those in which new capabilities are added only when needed. These incremental changes require decisions to be made in the planning and operations of transportation systems.

This paper recalls the Axiomatic Design approach called transportation degrees of freedom, developed in Farid (2008), Baca *et al.* (2013), and Viswanath *et al.* (2013). A small case study illustrates the usefulness of this method in the planning and operations phases of transportation engineering. The reason for choosing Axiomatic Design over more established design methodologies is twofold: first, the transportation degrees of freedom are defined in terms of both the function and form of the evolving system architecture; second, it bridges the traditionally graph theoretic approach to the engineering design community.

The remainder of the paper proceeds as follows. The Background section provides the basis for the methodological developments and discussion to follow, with brief introductions to graph theory (van Steen 2010; Newman 2010; Lewis 2009), Axiomatic Design (Suh 2001), and transportation degrees of freedom (Baca *et al.* 2013; Farid 2008). The

Transportation Degrees of Freedom section then recalls previous work on transportation degrees of freedom (Baca *et al.* 2013; Viswanath *et al.* 2013) which is framed in a transportation system context. The Case Study section illustrates the methodological developments on a small subsection of the Mexico City public transportation system. The Planning and Operations in Transportation Systems section describes the reconfigurability applications of these measures in the planning and operations timescales. The Conclusions section summarizes the work and results, and suggests avenues for future work.

Background

This section summarizes the relevant existing literature and provides a foundation for the measures presented and implemented in the next two sections. Some concepts are necessary to proceed with the discussion. These are presented in three steps. The first gives a brief introduction to graph theory. The second introduces Axiomatic Design, with a particular focus on large flexible systems. The third discusses a taxonomy of transportation system degrees of freedom as presented in earlier work.

Graph Theory

Graph theory is an established field of mathematics. It has application in many fields of science and engineering where artifacts are transported between physical locations (van Steen 2010; Newman 2010; Lewis 2009).

Graph theory has found extensive usage in transportation networks. For decades, it has proven useful in providing abstractions of transportation systems for operations research. However, it has limitations from an engineering design and systems engineering perspective. The graph theory definitions focus on the abstract form of the transportation system and not on the transportation functions or how they are realized. Such approaches are likely to have limitations in systems of heterogeneous function and form. Furthermore, “because the system function and its realizing form have been abstracted away, such approaches may not lend themselves to active control solutions that implement reconfigurable transportation system architectures” (Baca *et al.* 2013).

Axiomatic Design

Axiomatic Design is a systems design methodology developed by Dr. Nam Pyo Suh at the Mechanical Engineering Department at MIT in the 1970s. It was first published in 1978 and derives its name from the use of design axioms – laws for which there is no proof, but also no counter-proof - governing the analysis and decision-making process in the design of high quality products or systems.

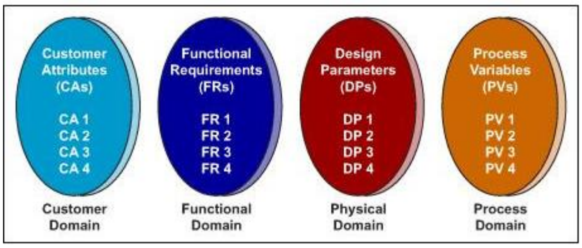

Figure 1. The four domains of Axiomatic Design (adapted from Suh 2001)

There are two fundamental concepts in Axiomatic Design: domains and design axioms. There are four domains – illustrated in Figure 1 - which explicitly describe the design activities that must be followed: first, understand the customer’s needs (in the customer domain, in the form of customer attributes or CAs); second, define the problem that must be solved (in the functional domain, in the form of functional requirements or FRs); third, create and select a solution (in the physical domain, in the form of design parameters or DPs); fourth, analyze and optimize the proposed solution (in the process domain, in the form of process variables or PVs). Finally, the resulting design can be checked against the customers’ needs, thus completing the design cycle. Decisions in one domain are mapped onto the domain on its right. In other words, for each pair of adjacent domains, the left represents “what we want to achieve” while the right represents “how we propose to achieve it”.

The second fundamental concept of Axiomatic Design is the two axioms for which this method is named. They are formally defined as follows:

Definition 2. The Independence Axiom: The independence of functional requirements must always be maintained (Suh 2001).

Definition 3. The Information Axiom: The information content of the design must be minimized.

The Independence Axiom can be reinterpreted as choosing FRs and DPs in such a way that a specific DP can be adjusted to satisfy its corresponding FR without affecting other FRs. The Information Axiom can be reinterpreted as choosing, among those designs that satisfy the Independence Axiom, the one with the maximum probability of success.

The mapping between domains can be represented by a design matrix, which shows the relationship between FRs and DPs, or between DPs and PVs. For the former, the design matrix is commonly known as the knowledge base of the system and is a fundamental part of the measures implemented in this paper.

In contrast to graph theory, Axiomatic Design of large flexible systems provides a natural engineering design description of transportation systems (Baca *et al.* 2013). Suh (2001) defines large flexible systems as systems with many functional requirements that not only evolve over time, but can also be fulfilled by one or more design parameters. In transportation systems, the set of functional requirements is taken as the set of transportation processes, **FR** = {Transportation Processes}. The set of design parameters is taken as the set of transportation resources **DP** = {Transportation Resources}. The definitions of a transportation process and transportation resource are adapted from Farid (2008) where they were used in a production system context.

Definition 4. Transportation Process: A transportation resource-independent process $p_u \in P$ that transports individuals between stations.

Definition 5. Transportation Resource: A vehicle $h \in H$ capable of realizing one or more non-null transportation processes such as a bus or train.

Axiomatic Design has been previously applied in the design of road intersections (Pena *et al.* 2010; Thompson *et al.* 2009a, 2009b; Yi and Thompson 2001), airport terminals (Pastor and Benavides 2011), and shipping companies and ports (Celik *et al.* 2009a, 2009b; Kulak 2005). The work in this paper expands the scope to include the entire transportation system network.

Once the high-level functional requirements and design parameters have been established, they may be simultaneously decomposed to establish full functional and physical hierarchies as part of a rigorous engineering design process. A civil engineering example of such work may be found in Gilbert III *et al.* (2013a, 2013b). While this goal is not the objective of this paper, establishing the measures presented in this paper in terms of the evolving high-level system architecture variables in both function and form grounds the methodology within the engineering design literature.

Mechanical Degrees of Freedom

The concept of degrees of freedom as applied to large flexible systems comes from previous work in the field of automated reconfigurable manufacturing systems (Farid 2007, 2008) where an analogy was drawn between mechanical and production degrees of freedom. The analogy is redrawn in Baca *et al.* (2013) and Viswanath *et al.* (2013) for transportation systems, and is recalled in this subsection.

At its most basic level, a mechanical system is defined by links and coordinates (Shabana 1998). Links make up the physical composition of the mechanical system; coordinates are used to express the evolution in time of a continuous state which results in motion. The physical form of transportation systems takes the form of transportation resources. Regarding the time evolution of transportation systems, an event-driven evolution of discrete states is more appropriate for the system architecture analyzed in this paper (Cassandras and Lafortune 1999).

The degrees of freedom of a multi-body mechanical system come from its links (physical composition) and coordinates (possible dimensions of a change of state). It is calculated as the number of links times dimensions minus any applicable constraints (Shabana 1998). Analogously, the degrees of freedom of transportation systems will come from the combination of feasible transportation processes and their associated resources minus any applicable constraints (Baca *et al.* 2013).

Mechanical degrees of freedom are classified as either scleronomic, i.e. time-independent, or rheonomic, i.e. time-dependent (Shabana 1998). For event-driven systems' degrees of freedom, they will be scleronomic or rheonomic in relation to their sequence dependence (Baca *et al.* 2013).

Transportation Degrees of Freedom

This section recalls previous work on transportation degrees of freedom (Baca *et al.* 2013; Viswanath *et al.* 2013; Farid 2008) which arises from the Axiomatic Design knowledge base for large flexible systems. First, the transportation system is defined to provide a clear problem definition. Next, the measure of scleronomic transportation degrees of freedom is presented as a quantitative indicator of the sequence-independent capabilities of the transportation system. Then, the rheonomic transportation degrees of freedom measure is included to address sequence-dependent system capabilities. Finally, the passenger degrees of freedom measure is recounted.

Problem Definition

A transportation system is composed of a set of transportation processes $P = \{p_1, \ldots p_{\sigma(P)}\}$ that transport passengers from an arbitrary station b_{y1} to b_{y2}, where the σ() gives the size of a set. If B is taken as the set of stations, then by definition there are $\sigma^2(B)$ such processes. Of these, $\sigma(B)$ are "null" processes where no motion occurs (i.e. going from station 1 to station 1).

These transportation processes are realized by a set of resources $R = \{r_1,\ldots,r_{\sigma(R)}\}$. An event $\varepsilon_{uv} \in E$ (in the discrete event system sense) (Cassandras and Lafortune, 1999) can be defined for each feasible combination of transportation process p_u being realized by resource r_v.

The transportation system knowledge base describes the transportation system's capabilities and is defined formally as follows:

Definition 6. Transportation System Knowledge Base: A binary matrix J_S, of size $\sigma(P) \times \sigma(R)$, is defined, where element $J_S(u,v) \in \{0,1\}$ is equal to one when event e_{uv} exists (Baca *et al.* 2013).

Interestingly, the Axiomatic Design knowledge base itself forms a bipartite graph (van Steen 2010) between the set of processes (e.g. functional requirements) and resources (e.g. design parameters).

Scleronomic Transportation Degrees of Freedom

The scleronomic transportation degrees of freedom, developed by Baca *et al.* (2013), Viswanath *et al.* (2013), and Farid (2008), are defined formally as follows:

Definition 7. Scleronomic Transportation Degrees of Freedom (Farid 2007, 2008): The set of independent transportation events E_S that completely defines the available transportation processes in a transportation system. Their number is given by:

$$DOF_S = \sigma(E_S) = \sum_{u}^{\sigma(P)} \sum_{v}^{\sigma(R)} \left[J_S \ominus K_S \right](u,v) \quad (1)$$

where Ks is the scleronomic constraints matrix of size $\sigma(P) \times \sigma(R)$ whose elements $K_S(u,v) \in \{0,1\}$ are equal to one when a constraint eliminates event e_{uv} from the event set. Such constraints can arise from any phenomenon that reduces the capabilities of the transportation system, such as vehicle breakdowns, line closures, or road detours. The $\ominus$ operator is equivalent to Boolean subtraction or A·not(B). Equation 1 can be rewritten in matrix form (Abadir and Magnus 2005):

$$DOF_S = \langle J_S, \bar{K}_S \rangle_F = tr(J_S^T \bar{K}_S) \quad (2)$$

The scleronomic transportation degrees of freedom measure allows the usage of the Axiomatic Design knowledge base for further detailed engineering design (Baca *et al.* 2013). Furthermore, the constraints matrix captures the potential for operational and planning constraints. As a result, it provides a flexible expression of the transportation system architecture and its capabilities in the planning and operational phases.

Rheonomic Transportation Degrees of Freedom

The previous subsection recalled the independent transportation degrees of freedom measure. However, a transportation system is inherently constrained by sequence-dependency. Rheonomic transportation degrees of freedom, also developed by Baca *et al.* (2013), Viswanath *et al.* (2013), and Farid (2008), are formally defined as follows:

Definition 8. Rheonomic Transportation Degrees of Freedom (Farid 2007, 2008): The set of independent transportation strings Z that completely describes the transportation system language. Their number is given by:

$$DOF_\rho = \sum_{u_1}^{\sigma(P)} \sum_{u_2}^{\sigma(P)} \sum_{v_1}^{\sigma(R)} \sum_{v_2}^{\sigma(R)} \Big[[J_S \cdot \bar{K}_S](u_1,v_1) \cdot [J_S \cdot \bar{K}_S](u_2,v_2) \cdot \bar{C}_\rho(u_1,u_2) \Big] \quad (3)$$

where C_ρ is

$$C_\rho(u_1,u_2) = \begin{cases} 0 & \text{if } \mathrm{mod}((u_1-1),\sigma(B)) = \\ & (u_2-1)/\sigma(B) \\ 1 & \text{otherwise} \end{cases} \quad (4)$$

Further matrix-based simplifications of this measure may be found in Baca *et al.* (2013), Viswanath *et al.* (2013), and Farid (2013). Note that this definition considers two transportation degrees of freedom in a sequence. Mathematically speaking, for one degree of freedom to follow another, the destination of the former must be equivalent to the origin of the latter. Intuitively speaking, certain transportation events may follow one another, while other combinations are not possible. The rheonomic transportation degrees of freedom provide a sequence-dependent measure of the capabilities of the transportation system.

Passenger Degrees of Freedom

The passenger degrees of freedom measure was developed from the scleronomic and rheonomic transportation degrees of freedom. It measures the number of ways that a passenger in the transportation system may be transported from a desired origin to a final destination (Baca *et al.* 2013). It is defined formally as follows:

Definition 9. Passenger Degrees of Freedom (DOF_p): The number of passenger itinerary strings in the language L_ρ between a desired origin y_1 and a desired destination y_n (Baca *et al.* 2013). Their number is given by:

$$DOF_p = \sum_{i}^{n} DOF_{pi} \quad (5)$$

where it is equal to the sum of itineraries consisting of 1 leg, 2 legs, up to the number of n legs deemed practical by the passenger. The number of one leg routes uses the scleronomic degrees of freedom measure in Eq. 1, while the number of two-leg routes uses the rheonomic transportation degrees of freedom found in Eq. 3. In both cases, the scleronomic constraint matrices must be updated to incorporate both the desired origin y_1 and the desired destination y_n. The same logic used to derive Eq. 3 from Eq. 1 follows for 3-leg and up to n-leg journeys. The scleronomic constraint matrices would have to be similarly updated. For the number of n-leg routes –i.e. the number of n-event rheonomic transportation degrees of freedom, $DOF_{\rho n}$

$$= \sum_{u_1,\ldots,u_n}^{\sigma(P)} \sum_{v_1,\ldots,v_n}^{\sigma(R)} \left[\prod_{x}^{n-1} [\mathrm{J}_s \cdot \bar{\mathrm{K}}_s](\mathrm{u}_x, \mathrm{v}_x) \cdot \bar{C}_\rho(u_x, u_{x+1}) \right] \tag{6}$$
$$\cdot [\mathrm{J}_s \cdot \bar{\mathrm{K}}_s](\mathrm{u}_n, \mathrm{v}_n)$$

The calculation of this formula may be greatly facilitated using the graph theoretic methods provided in Baca *et al.* (2013), Viswanath *et al.* (2013), and Farid (2013).

This section recalled the methodological developments presented in Baca *et al.* (2013) and Viswanath *et al.* (2013). The scleronomic and rheonomic transportation degrees of freedom were used to model passengers in terms of transportation sequences. The final measure, passenger degrees of freedom, allows for the enumeration of passenger itineraries. All three measures exhibited the same common elements also found in mechanical degrees of freedom: discrete events captured in Axiomatic Design knowledge bases, constraint matrices, and a Boolean difference of these two matrices.

Case Study: Mexico City Public Transportation System

Baca *et al.* (2013) and Viswanath *et al.* (2013) used a subsection of the Mexico City Public Transportation System to demonstrate the passenger itinerary enumeration made possible by the passenger degree of freedom measure. This same system is once again used to illustrate the usefulness of the methodological developments of this paper – this time, the planning and operations applications of the passenger degree of freedom measure.

For purely illustrative purposes, the system boundary is narrowed down to a few square blocks around the City Center (Zocalo area), which is considered to be the exact geographic center and hub of activity in the city. This reduces the system from over 300 stations to a much more manageable 9 stations within the system boundary. A smaller example provides a better understanding of the relevant principles without any loss of generality or extensibility to systems of larger size (Baca *et al.* 2013).

The knowledge base for the defined system is an 81x2 binary matrix, J_S. The rows represent the possible transportation processes between stations (9 stations, 9^2=81 FRs), including same-station FRs. The columns represent the transportation resources (in this case, the two transportation modes: Metro and Metrobus). By definition, the transportation process is equal to 1 if there exists at least one resource capable of realizing it within the given window of time. The time scale is adjusted throughout depending on the application and the desired measurement, which is another advantage of using an Axiomatic Design-based approach.

Number of Passenger Itineraries

The scleronomic and rheonomic (2-leg) transportation degrees of freedom for this given system were found to be 56 and 422, respectively, within a 1-hour timescale. In other words, 56 out of the 81 transportation processes were achievable with a 1-leg journey (including same-station FRs). This high number can be explained by the small area of the example. Also, 422 itineraries of 1 and 2-leg journeys were possible between the 9 stations (again, including same-station FRs) – journeys of 3 legs or longer are ignored, under the assumption that passengers would consider them no longer practical within such a small geographic area.

The number of passenger itineraries, while a powerful quantitative measure of the capabilities of the system, is only one of many system measures that can be derived from the transportation degrees of freedom. The next section provides a discussion of some of these applications.

Planning and Operations in Transportation Systems

Axiomatic Design has proven to be a powerful tool for developing transportation degrees of freedom as a measure of reconfiguration potential. This section discusses four classes of applications for these developments: redundancy and flexibility, reconfigurable operations, reconfigurable planning, and reconfigurability valuation.

Redundancy and Flexibility

The terms ‘redundancy’ and ‘flexibility’ are ubiquitous in the engineering design field. Flexibility is a valued property in systems and one of the major “ilities” in systems engineering (de Weck *et al.* 2011). Redundancy, on the other hand, is often maligned by designers and engineers alike. Redundancy in the physical composition of a system is undesirable as it adds costs and complexity, but does nothing to improve system functionality. While this is true of most systems, transportation systems require some measure of redundancy. Redundancy is a critical component of resilience, which itself reflects the uncertain nature of transportation systems. How much redundancy is required by transportation systems makes for an interesting research topic to be sure, but is not the focus of this paper.

The Axiomatic Design knowledge base provides a measure of redundancy and flexibility. The sum of the non-zero elements in each column of the knowledge base serves as a measure of flexibility of the given transportation resource. The sum of the non-zero elements in each row provides a measure of redundancy for the given transportation process (Farid 2008).

In the case study, redundancy becomes evident by the fact that the Metro and Metrobus share many stations. If the system were expanded to include all 300+ stations in the public transportation network, it would illustrate this claim even more strongly: most of the shared Metro/Metrobus stations are located at a high density near or around the City Center, which has the highest volume of passengers. This redundancy pays dividends on a regular operational viewpoint by providing alternatives to passengers and much-needed relief for the most congested lines and times. In the event of an unplanned failure, redundancy is necessary to ensure that the most important routes are still being realized by the available transportation resources. Furthermore, redundancy enables another life cycle property, namely resilience. In unforeseen natural disasters such as hurricanes and floods, redundancy allows for rapid evacuation and enhanced emergency services.

Redundancy may take different physical forms. There are many public transportation systems around the world that build parallel tracks for their subway lines, which allows them to run more than one train at a time. Others, meanwhile, build different lines that run along the same route for long distances. The Tokyo subway is a good example of the former; the New York City subway, of the latter. The transportation degree of freedom approach allows the representation of both cases, since there is a remarkable amount of freedom in how the functional requirements and design parameters are represented in the knowledge base. For the case study, the DPs were defined as transportation modes. Individual tracks, road lanes, trams, and/or buses could have been used instead to give a more granular view. Additionally, the timescale can also be adjusted to a minute-by-minute scale for real-time operation or on a daily scale for a more temporally coarse measure of transportation capabilities.

Reconfigurable Operations

The scleronomic transportation degree of freedom provides a quantitative measure of the system capabilities and how they can be changed. The rheonomic transportation degree of freedom provides a quantitative measure of how system capabilities can be combined into sequences. In both cases, these measures describe the impact of these reconfigurations on the system capabilities.

The concept of transportation degrees of freedom can be applied to achieve reconfigurable system operations (Baca *et al.* 2013) when the knowledge base and constraint matrices are used over a short and regular time interval - i.e. one hour - a reconfiguration process can be said to occur from one hour to the next. One such example is bus and metro lines that are not operational throughout the entire day; their period of non-operation can be captured in the constraints matrix. Unplanned disturbances and breakdowns can also be captured at the operational timescale.

There are many types of constraints that can limit the reconfiguration potential of the transportation system. Fixed schedules are an example of inflexible operations. Buses and trains leave at a fixed time from a fixed location, regardless of existing traffic conditions or irregularities elsewhere in the system.

Real-time operational control decisions are making their way into transportation systems in what are often called Intelligent Transportation Systems (Chowdhury and Sadek 2003). Active real-time switching in railways can be viewed as making real-time reconfigurations and may be aided by the Axiomatic Design knowledge base of the system. The Tokyo Metropolitan Traffic Control Center optimizes traffic flow in the city, making use of more than 15,000 vehicle detectors and 300 traffic information boards to regulate the flow of car traffic, pedestrian traffic, and public transportation. Real-time transportation scheduling algorithms are another key enabling technology for reconfigurable operations, and many of them use matrix-based mathematical programming methods similar to the transportation degree of freedom approach.

Reconfigurable Planning

The concept of transportation degrees of freedom can also be applied to medium and long-term planning decisions. In the medium-term, the schedules generated by system operators represent a planning activity in which transportation resources are allocated to achieve the transportation resources in the most efficient manner. In the Axiomatic Design language, this is akin to mapping design parameters (transportation resources) to the functional requirements of the system (transportation processes). In the long-term, planning decisions may include semi-permanently modifying the system's capabilities by adding or removing modes of transport, lines, or individual transportation resources (such as buses or trains). These changes to the transportation network are reflected in changes to the knowledge base, which can be expanded to include new transportation processes (i.e. rows in the knowledge base) and new transportation resources (i.e. columns in the knowledge base).

Returning to the Mexico City case study, Baca *et al.* (2013) showed how the flexibility and reconfigurability of the system increased dramatically with the introduction of the Metrobus in 2005. This was done by computing the passenger degree of freedom measure both before and after 2005. Many other measures of quality –passenger capacity, transit times, and greenhouse gas emissions, among others- are possible and addressed in the next subsection.

Premium on Reconfigurability

The concept of transportation degrees of freedom as a measure of reconfiguration potential draws questions about the value of this reconfigurability. To this end, it is important to recognize that each transportation degree of freedom can be associated with quantifiable measures of cost, benefit, as well as return on investment.

In the operational domain, each degree of freedom can be associated with a passenger capacity, passenger traffic, operating cost, and revenue. Alternatively, it can be associated with energy consumption, transit time, greenhouse gas emissions, and externalities (Baca *et al.* 2013). Returning to the case study, it is possible to adjust the capacity of the system by adding trains or buses. Employing this approach, these decisions can now be automated and conducted in a systematic fashion that facilitates deeper engineering design of automation and control systems.

In the planning phase, similar measures can be associated with each degree of freedom to determine the impacts of changing the system. The required investment to make the degree of freedom possible - and potential additional revenue earned from it - can aid in the long-term decision-making process. Similarly, such an approach can be used to model future energy consumption, greenhouse gas emissions, and transit times from a technical planning perspective. In the case of the Mexico City Public Transportation System, these planning calculations can be done after the fact to reveal interesting results. The passenger capacity, for instance, was calculated to increase by 35% in the defined subsystem with the introduction of the first Metrobus line in 2005. The greenhouse gas emissions were calculated to increase by 48% due to Metrobus buses being more energy efficient and running on dedicated surface streets (and, hence, not being stuck in traffic). The capacity growth figure matches the statistics provided by the Mexico City Transportation Authority in 2006 (35%), while the emissions reduction figure falls short by a small margin, 48% vs. 40% (Metro 2013).

This section has shown that it is possible to value reconfigurability as an operations stage life cycle property. Furthermore, it provides a measure of the long-term reconfiguration process in the planning phase, which can be valued in terms of time or monetary cost (Farid 2007).

Conclusions and Future Work

This paper has expanded on the planning and operations applications of the transportation degrees of freedom first developed in Baca *et al.* (2013). The work rests firmly on the foundation of previous work on production degrees of freedom (Farid 2007, 2008), which was contextualized to transportation processes and resources. The application-neutral Axiomatic Design model of a knowledge base of functional requirements and design parameters explicitly represents the transportation system - with its associated processes and resources - and its constraints in matrix form.

The transportation degree of freedom measures come in two varieties. The scleronomic degrees of freedom assess available transportation processes irrespective of sequence. The rheonomic degrees of freedom consider path dependency. These measures and their applications were discussed practically, extending the Mexico City case study from Baca *et al.* (2013). These measures showed how the reconfiguration potential of the Mexico City public transportation network changed in the face of additional resources. It also represented potential reconfigurations in which stations were added, modified, or removed. These measures also show that many insights into the system structure can be gained if the allocation of processes is considered in relation to resources. In this way, they provide a thorough understanding of the potential for reconfiguration in large flexible systems - such as transportation networks.

From a theoretical perspective, the Axiomatic Design models have multiple advantages (Baca *et al.* 2013). From a modeling point of view, these models avoid any unnecessary information and can be decomposed and incorporated into design processes specifically aimed at achieving system resilience and reconfigurability (Baca *et al.* 2013). In an intuitive way, each element corresponds to a physical relationship that is fundamental to the desired reconfiguration. Furthermore, active control solutions can be developed that utilize the knowledge base and constraint matrices in the operational timescale.

In future work, the authors seek to develop reconfiguration “ease” measures (Farid 2007, 2008), which is the other half of the reconfigurability measurement question. Measurements of other key characteristics of systems, such as integrability and convertibility, also provide a challenging avenue of future work (Farid 2007). Finally, all these measures would benefit from their application in industrial case studies.

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