Chapter 22
Network Representations of Efficiency Analysis for Engineering Systems: Examples, Issues and Research Opportunities

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Abstract Network efficiency models depict internal production/service processes, and/or alternative perspectives, and/or different time periods. Researchers in the efficiency measurement field are investigating and applying these models in a variety of ways. However, in very few instances are these representations focused on engineering systems. This chapter presents two very distinct network efficiency models that are applied to engineering systems. The first uses the radial and slacks based network DEA models to assess the efficiency performance of a downtown space reservation system (DSRS). This system has been designed as an approach to mitigate traffic congestion in an urban downtown area. The implementation of the network DEA models identify the determinants of efficiency performance for the agency operating the DSRS, for the traveler using the DSRS and for the community where the DSRS resides. The second example pertains to asset management and more specifically to highway maintenance management. An alternative network efficiency representation is used where a system dynamics modeling approach provides a way to study dynamic efficiency performance and assess highway maintenance policies. Through these examples, issues pertaining to opening the production black box to evaluate internal processes, the validity of the axiomatic foundations of DEA for the network models, the relevance of the structure of the network models in terms of suggesting resulting system behaviors, temporal and dynamic efficiency performance associated with the network efficiency models are discussed suggesting future research directions.

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22.1 Introduction and Context

Even though efficiency measurement and improvement has been a significant area of scholarly research, engineers have not extensively used the efficiency measurement paradigm to evaluate system performance and design engineering systems (Triantis 2011, 2013) even though there are notable exceptions in the literature (e.g., Cooper et al. 1992).

There are number of issues that provide challenges and opportunities for this type of research. Typically, the focus of the analysis for engineering systems is at the very micro level. This suggests that the "input/output transformation box" typically considered in efficiency analyses needs to be "opened" and studied in detail. This requires access and understanding of the underlying technologies, processes, information exchange, organizational settings, and social/behavioral considerations. On a very fundamental level, from an engineering perspective, a first understanding of what needs to be measured lies in having a full appreciation and knowledge of the physical and engineering relationships that govern these systems.

However, engineering systems are not designed, built and operated in a vacuum. There are organizations and design teams that are tasked to do so by exchanging important information and making decisions. Given, this reality, understanding the interdependencies between system performance and the organizational entities that are responsible for these engineering systems is paramount. This suggests that we need a deeper appreciation and integration of the social/behavioral and information sciences in our measurement analyses and thinking.

While the efficiency literature is based on an axiomatic framework (Vaneman and Triantis 2003) the engineering design literature does not enjoy a similar axiomatic foundation. What this means is that while in efficiency measurement we rely on production theory, in engineering design the theory is still evolving while at the same time engineering design literature borrows knowledge and representations from organizational, optimization, decision, and probabilistic theoretical frameworks among others. At the end, we need to make sure that the axiomatic framework on which efficiency evaluation methods are based on are relevant for the specific systems that we are evaluating and designing.

An important consideration is when in the system life-cycle performance assessment is being conducted. Most efficiency studies rely on an ex-post assessment where historical performance is analyzed. For engineering systems, the evaluation of performance during design (conceptual, preliminary and detailed) (Blanchard and Fabrycky 2010) is just as important as the assessment of performance during operational phases. This performance evaluation during the design phase requires the identification of the production possibility space or the design possibility space and to make sure that the axiomatic framework underlying efficiency measurement still holds for the various systems being considered.

Related to the previous point, i.e., as to when in the system life cycle the performance analysis is conducted, are the temporal and dynamic considerations of system performance (Fallah-Fini et al. 2013a). In this chapter we borrow the dynamic concepts presented by Sterman (2000) that help describe the dynamic characteristics of systems. More specifically the concepts that we take into account is the consideration of causation, feedback mechanisms, delays, and non-linear relationships. In our dynamic representations and models the structure of the system leads to the observed dynamic system behaviors and the resulting system performance.

In this chapter, we build on the concept of networks in efficiency analysis and how this concept can be used to address some of the issues described in this Section. More specifically, in Sect. 22.2, we employ the notion of network DEA (both radial network DEA (Färe and Grosskopf 2000) and slacks based network DEA (Tone and Tsutsui 2009)) in the context of a transportation system that has yet to be designed, i.e., the downtown space reservation system (Zhao et al. 2010a, 2011). The DSRS uses concepts from transportation engineering and efficiency measurement and combines system optimization, neural networks, traffic micro-simulation and network DEA approaches.

Additionally, in Sect. 22.3 we provide a description of a different type of network that considers the dynamics of highway maintenance (Fallah-Fini et al. 2010). The highway maintenance example combines concepts from highway deterioration and efficiency measurement and combines system dynamics simulation, optimization and efficiency measurement. In both of these sections we do not replicate the details of the mathematical formulations, models and discussions in the papers that have already been published or are under review. However, we do wish to highlight some of the issues that have been briefly described in this section and focus on future research opportunities (Sect. 22.4).

22.2 The Downtown Space Reservation System (DSRS)[1]

22.2.1 The Initial DSRS Conceptualization

In transportation engineering, congestion analysis is a continuing research concern. Travel demand based approaches attempt to reduce congestion by defining, evaluating, and implementing congestion mitigation strategies. An experimental travel demand management approach that has yet to be implemented is the downtown space reservation system (DSRS) (Zhao et al. 2010a) whose main objective is to mitigate downtown traffic congestion.

Within the DSRS, travelers who want to drive to an urban downtown area have to reserve their time slots in advance before embarking on their trips.

[1] This section is adopted from Zhao et al. (2010a, b, 2011).

The transportation agency who operates the DSRS, allocates time slots to travelers based on the availability of the road network capacity. Only the travelers who get permission from the transportation agency can drive in the downtown area during the requested time period. This system is analogous to the idea of making reservations in advance to secure a seat on an airline for a trip taking into account carrier capacity. In the case of the DSRS, the traveler is securing a time slot to visit the downtown area taking into account road capacity.

The proposed DSRS consists of two modules, an offline optimization module and an online decision making module (based on a neural network approach). In the offline module, an optimization model is solved based on historical travel information. Two objectives are included in the optimization problem, i.e., the total number of travelers that the transportation system handles during a certain time period and the revenue obtained from the downtown space reservation system. From a travel demand mitigation point of view, the mobility of people is improved by restraining the excessive amount of automobiles entering the downtown area. From an economic point of view, revenue is maximized. It is assumed that this revenue can be used to finance public transportation systems.

In order to take into account the stochastic variations in travel demand, a neural network approach was used to construct the online module. Assuming that we have hundreds of historical demand scenarios, we obtained optimal solutions for each scenario (using the CPLEX platform). Given that artificial neural networks have the capability to "learn from experience" (Teodorović and Vukadinović 1998), they can be taught from the historical demand scenarios and the derived optimal solutions. From this learning process, the system is able to recognize a situation characterized by the number of reservations that already have been made for each vehicle class during each time period and the corresponding revenue generated from the reservations. Therefore, when a new request comes in, the neural network can rely on this historical information to provide a real time decision. In addition, new requests become historical information and the system can be updated at predetermined time intervals.

22.2.2 The Micro-simulation Evaluation

From a system performance measurement point of view, there were a number of challenges. First is the fact that there were no ex-post data to use for the performance analysis. The DSRS has been proposed but not yet implemented so there were no available historical operational data. Second, the level of aggregation at which the performance analysis could take place needed to be decided.

Initially, Zhao et al. (2010b) used a microscopic traffic simulation approach executed in VISSIM to evaluate the DSRS. The microscopic traffic simulation emulated the physics of traffic flow at a microscopic level. The simulation was conducted for a revised road network representing downtown Boise, Idaho. The issues that were tested in the simulation included: whether the DSRS improves traffic performance when compared without the DSRS; how the DSRS performs compared with a reservation system that uses the First Come First Serve (FCFS) principle; how specific DSRS parameters (such as, the relative importance of traveler throughput versus revenue generation) influence the transportation network system performance. The performance parameters that were outputs from the simulation included typical engineering variables such as: average delay time per vehicle, average speed, total travel time, total vehicle miles, total delay time, fuel usage and costs, and emissions.

22.2.3 Social Welfare Evaluation for the Three Perspectives

Yet in addition to the standard transportation engineering measures of performance one is faced with issues related to performance from the agency's/provider's, travelers'/users' and community's points of view where the social welfare impact of the DSRS needs to be considered. These three perspectives represent important stakeholders in the transportation system and their interactions determine the overall performance of the transportation system. By social welfare we are suggesting that above and beyond the engineering traffic flow impacts of the DSRS, one needs to take into account the impact of the system as far as the operational issues associated with the transportation agency that is providing the service, the quality of service that is experienced by the travelers using the system and the sustainability issues insofar as the community is concerned.

At the initial stages of the DSRS development (Zhao et al. 2010a), the design of the system was anchored around the objective of mitigating congestion. This means that the original optimization model, which is at the core of the DSRS, was not formulated to consider multiple stakeholder perspectives (agency, traveler, community). In order to consider these multiple perspectives, the network DEA approach was considered as a potentially viable approach. Nevertheless, there were a number of issues that needed to be resolved as the following section suggests.

22.2.4 The Network DEA Approach

22.2.4.1 Assumptions and Considerations

As stated in the Sect. 22.1, the production possibility space or in this case the design possibility space needed to be defined. This required the determination of the decision making units and the definition of the inputs and outputs associated with each of the three perspectives (agency, traveler, and community). Additionally, it was assumed that the production axioms (Vaneman and Triantis 2003) governing the inputs and outputs held as part of the associated service processes that are part of the three perspectives. The three processes in the context of this research are the service provision process of the transportation agency, the service consumption process of the travelers, and the environmental impact process for the community as a function of automobile travel in the downtown area.

An understanding of each of these processes provided the requisite background to define the input and output variables that were used in the network DEA model that linked the three perspectives. It was assumed that the system was being evaluated at the beginning of the system life-cycle. The dynamics associated with the various processes of the DSRS and the impact of organizational/behavioral/ information issues (e.g., the way the transportation agency would implement the DSRS) were not considered as part of the measurement evaluation. An open issue that still remains unresolved was how to account for the fact that the DSRS is to be used by many travelers. The network DEA approach assumed that for the travelers' perspective we would consider average values associated with multiple travelers for the input and output variables that were defined for the traveler perspective. This aggregation issue however, requires further investigation in the future.

The essence of the network DEA efficiency measurement approach was to compare and contrast various instances (scenarios) that occur in the transportation network under the execution of the Downtown Space Reservation System (DSRS). The scenarios constituted the production possibility set for our analysis. In other words, the scenarios generated by the traffic micro-simulation constituted the decision making units (28 in total). In this context, the data that were used were viewed as ex-ante versus ex-post data.

The scenarios varied in terms of the total demand level (i.e. number of vehicles per control period), the reservation policies (i.e. the weights assigned to the traveler throughput and revenue in the objective function of the optimization model (Zhao et al. 2010a)) and the inherent stochastic behavior of the traffic assignment and the traffic flow in the simulation. The demand level varied from 6,000 to 7,000 (vehicles/control period) and was chosen according to the transportation network size of the traffic simulation model. The relative importance (and consequently weights of the DSRS optimization model) associated with the traveler throughput and revenue was arbitrarily assigned due to the lack of practical references. Operational costs were assumed constant for all of the 28 DMUs. The data from the simulation model were complemented with revenue data from the original optimization model of the DSRS.

22.2.4.2 The Network DEA Approach: The Initial and Final Representations[2]

The idea behind the network DEA formulation is that users and community stakeholders are likely to be outcome oriented whereas providers are output oriented. Furthermore, we assumed that users are more focused on their mobility and

[2] The mathematical formulations for the radial and slacks-based network models are described in Zhao et al. 2011.

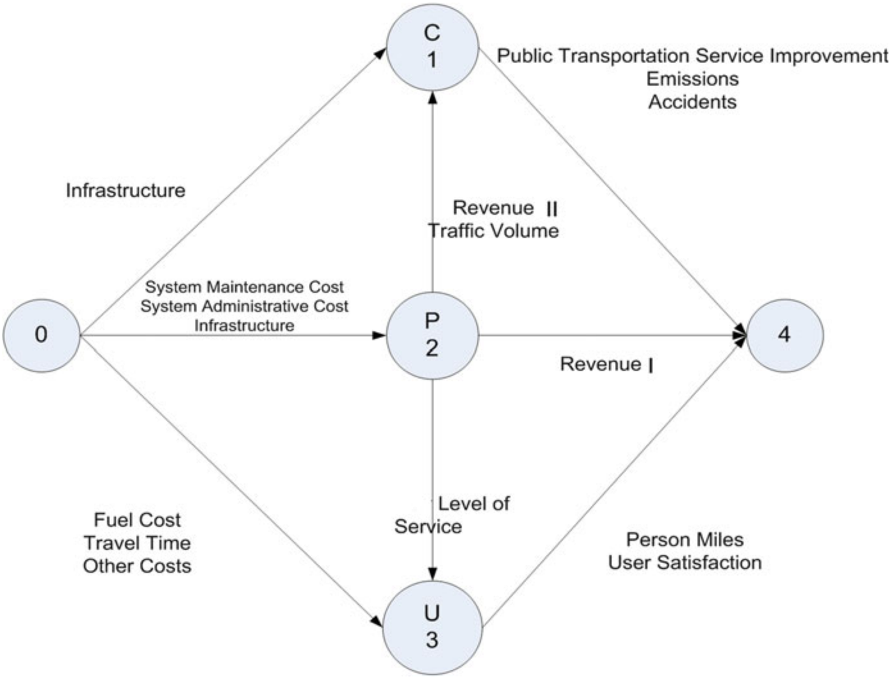

Fig. 22.1 Three perspectives of the performance network structure (initial conceptualization) (Reprinted with permission from Zhao et al. 2011)

this was reflected with the travel time related measures. It was assumed that transportation agencies are mostly concerned with system efficiency and effectiveness, which is reflected by the revenue, the level of service, and the vehicle miles traveled. Last but not least, the community typically is concerned with environmental and safety issues that are associated with traffic. Therefore, sustainability oriented measures (such as, emissions) are more appropriate to reflect their interests.

The network of Fig. 22.1 represents the conceptual underlying structure of the DSRS transportation system with respect to the three perspectives and their interrelationships. This initial conceptualization was arrived at from input from transportation engineers. The network consists of five nodes. Node 0 and node 4 are dummy nodes. The purpose of these nodes is to distribute inputs to and collect outputs from the intermediate nodes (nodes 1, 2 and 3). Therefore, the performance of the network reflects the interrelationship among the three perspectives captured by nodes 1, 2, and 3. Node 1 represents the community's perspective that is directly impacted by the transportation system. Node 2 represents the viewpoint of the transportation service provider whereas node 3 is the transportation user's perspective. The connection between nodes is directed, indicating the material transformation from inputs to outputs.

From the agency's perspective, the inputs to the transportation system include different operational costs and the transportation system infrastructure. The operational costs considered in this research are the system maintenance and administrative costs that the transportation agency wishes to minimize. It is also assumed that the agency makes decisions on whether to improve the transportation infrastructure, so it is considered as an input to the agency node 2. The outputs from the agency node 2 include revenue (Revenue I and II in Fig. 22.1), traffic volume, and level of service (LOS). While collecting revenue (Revenue I) to maintain the transportation system is in itself an objective for the agency, revenue (Revenue II) is also collected as a final output. It is assumed that traffic flow on the roads will result in traffic volume as a consequence of the DSRS and thus this variable is considered as an output from the agency's node 2. LOS is included as an output for node 2, because one of the agency's goals is to provide a certain LOS to the traveler.

From the community's point of view, the inputs are the infrastructure, the revenue (Revenue I) from executing the DSRS and the traffic volume. Infrastructure is imposed in the community's territory, so it is viewed as an input for node 1. The traffic volume will result in emissions and accidents for the community, and we assume that part of the revenue (Revenue I) from the DSRS will be used to improve the transit system in the community. Thus, the traffic volume and revenue (Revenue I) are included as inputs to the community node, and emissions (undesirable output), accidents (undesirable output) and public transportation improvements (desirable output) are the outputs.

From the travelers' perspective, the fuel cost, travel time and other costs including the reservation fee spent on the trips are considered as inputs by most travelers. These costs are direct costs. Since node 3 reflects the traveler's perspective, the measurement of the output is considered to be person miles rather than vehicle miles therefore the outputs from node 3 are person miles traveled and user satisfaction. Among all the variables in the representation of Fig. 22.1, there are two types of inputs/outputs – intermediate inputs/outputs and initial inputs/final outputs. The final outputs are the outputs that are accumulated in node 4, such as emissions, accidents, and person miles. The intermediate outputs, LOS, traffic volume and revenue, are the outputs from agency's node 2 and they are also the inputs to nodes 1 and 3.

Given the data from the micro-simulation model and from the original DSRS formulation the network DEA representation that was finally executed is represented by Fig. 22.2. Travel time, vehicle miles, average speed, fuel costs, emissions and personal miles (calculated from total vehicle miles and average occupancy) was obtained from the micro-simulation whereas revenue was obtained from the DSRS optimization. Radial network DEA and slacks based network DEA models were computed for the network (both input and output orientations) whereas the Banker et al. (1984) efficiency scores were computed for each of the nodes (Fig. 22.3). The reason why the efficiency scores for each of the individual nodes were computed was to determine the differences in performance evaluation using the network DEA and the DEA individual formulations.

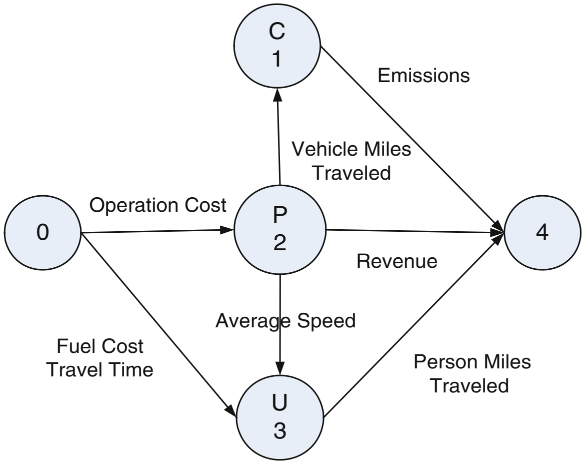

Fig. 22.2 Three perspectives of the performance network structure (final representation) (Reprinted with permission from Zhao et al. 2011)

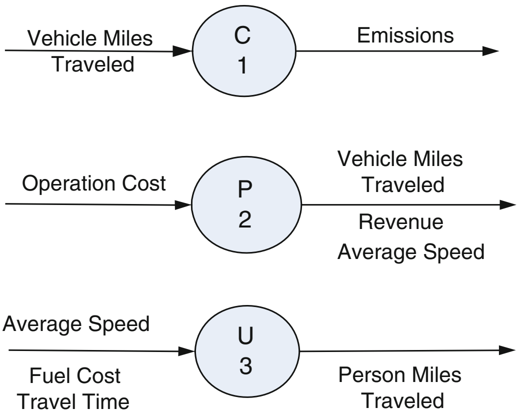

Fig. 22.3 Single node representations for each perspective (Reprinted with permission from Zhao et al. 2011)

22.2.5 Network DEA: Conclusions from the Example

The differences between the radial network and slacks based models for this example lie in the way the efficiency scores are computed. The radial and the slacks based model network DEA approaches provide different performance assessments. For example, when considering both approaches, the node that dominates is different given that the radial network efficiency score focuses primarily on the relatively efficient node in the network and ignores the inferior performance of the other nodes. Whereas, the slacks based network measure considers the average performance of all nodes. According to this information, the decision maker may be inclined to focus on very different interventions so as to improve system performance. For instance, based on the results from our example, the radial network DEA will lead the decision maker to focus more on the agency's perspective, while the slacks based network model will lead decision maker to focus on the traveler.

One of the core assumptions is that the network DEA structure is representative of the underlying processes (in this example, transportation processes (from an agency's and traveler's points of view) and community processes (in terms of community resilience). The network structure assumes two things. The first is that the input and output variables considered for each node are accurate representations of the service transformation processes. The second is that the interactions (co-dependencies) between nodes are reflected by the intermediate inputs and outputs. This means that other forms of co-dependencies (physical, informational and behavioral) are not at explicitly considered.

This research uses a combination of a DSRS optimization, a neural network, a micro simulation evaluation and a network DEA approaches. What this suggests is that when evaluating alternative system designs it is reasonable to combine analytical with simulation approaches. In our example, the DSRS optimization model itself could not convey important information, such as which traffic flow conditions are best suited for the DSRS, whether the design of the system meets stakeholders' requirements, and how the DSRS influences agency, traveler, and community performance. This is why it was necessary to additionally execute the micro-simulation and network DEA approaches.

Simulation is one of the most popular tools used by transportation engineers. It has been used to test and analyze the DSRS (Zhao et al. 2010b). The simulation model provides various transportation measures (e.g. travel time, average delay, etc.) and helps the decision maker appreciate the system from a transportation engineering perspective. However, additional performance aspects need to be considered. For example, the simulation does not directly tell us how various input/output variables affect overall system performance and whether social welfare goals are met by key stakeholder entities. The network DEA approach provides a single index as representative of the overall system efficiency and identifies appropriate sources of inefficiency across the various perspectives.

Therefore, the DSRS optimization model represents the system that was designed; the simulation and the network DEA models are the supporting approaches that provide an assessment of this system design. The two evaluation approaches are complementary. The simulation approach supports the network DEA model by providing data, and the network DEA performance measurement complements the simulation model by taking into account the key perspectives that are impacted by the potential implementation of the DSRS.

Returning to the discussion of Sect. 22.1, the network DEA approach helps the decision maker understand the system that is being evaluated by opening the DEA transformation "black box". This enables decision makers to locate the sources of inefficiency more precisely. For example, if the network DEA model shows that inefficiency is linked mainly to the traveler, the decision maker might improve the traveler throughput via a pricing policy adjustment. Additionally, we assumed that the axiomatic framework on which DEA is based holds for each of the three nodes of our example and for the network as a whole. Nevertheless, we did not consider the dynamic characteristics of the DSRS system which brings us to the next topic in this chapter.

22.3 Dynamic Representations of Performance Measurement Networks

While the static network DEA performance models for engineering systems provide an initial understanding of the determinants of efficiency performance within these systems, they do not consider the dynamic characteristics of these systems. In terms of dynamic network performance models, the efficiency research community has chosen to approach this issue using two distinct and separate directions.

The first simply extends network DEA formulations to include time (see for example, Tone and Tsutsui 2013). An alternative approach is to model the system's dynamic behavior explicitly (for example, using either system dynamics (Vaneman and Triantis 2007) or agent based modeling (Dougherty et al. 2013)) and then include efficiency concepts as a way to assess system performance. This latter direction allows for the explicit consideration of causation, feedback mechanisms, delays, and non-linear relationships whereas the former direction introduces temporal variations of efficiency measures explicitly. As described in the example of Sect. 22.2, the structure of network DEA model does not suggest anything in terms of the resulting system behavior whereas, the structure of system dynamics or agent based models result in various forms of system behaviors once one executes the simulations. On the other hand, the ways to measure efficiency performance with the system dynamics (Fallah-Fini et al. 2013b) or agent based models (Dougherty et al. 2013) are not straightforward. Consequently, one can view both directions as complementary since they address alternative representations of dynamics and efficiency measurement.

In order to complement the discussion of Sect. 22.2 we offer an example of a system dynamics representation of a system where performance assessment is an important objective. In the example that follows we use system dynamics to explicitly consider highway deterioration and renewal and briefly describe how efficiency measurement considerations are incorporated. The modeling details are described in Fallah-Fini et al. (2010, 2012, 2013b) which we do not replicate in this brief overview.

22.3.1 Infrastructure Management: Obtaining an Optimum Strategy for Road Maintenance[3]

For the highly challenged U.S. road infrastructure, major budgetary restrictions at the State and Federal levels and the significant growth in traffic demand have led to a continual pressure to improve the performance of highway maintenance practices. This has led to a series of analyses (Fallah-Fini et al. 2010, 2012, 2013b) that have

[3] This section is adopted from Fallah-Fini et al. (2010, 2012).

attempted to assess the privatization of road maintenance operations by state Departments of Transportation (DOTs). The research findings of these studies have indicated that road agencies should use hybrid contracting approaches that include best practices of both traditional (public) and performance-based (private) highway maintenance contracting. The analyses used an empirical dataset of pavement condition and maintenance expenditures over the years 2002–2008 corresponding to 17 miles of interstate highway that lay in one of the counties in the state of Virginia, USA. The data allowed for the calibration of the developed system dynamics models.

In the dynamic efficiency measurement model (Fallah-Fini et al. 2013b) the performance of highway maintenance operations was evaluated where the intertemporal dependences between consumption of inputs (i.e., maintenance budget) and realization of outputs (i.e., improvement in road condition) were explicitly captured. We built on a micro representation of pavement deterioration and renewal (Fallah-Fini et al. 2010, 2012) and studied the impact of the allocation of scarce maintenance budgets over time. We introduced a concept of efficiency that contrasts the optimized budget allocations to the actual ones. The policies that were found through the optimization showed that road authorities should give higher priorities to preventive maintenance than corrective maintenance.

Initially, in order to establish the basic model we identified key maintenance dynamics associated with road maintenance and then we represented the deterioration and renewal processes of road maintenance using a physical understanding of these processes at the pavement level. The deterioration and maintenance dynamics can be summarized in two major feedback loops (See the causal loop in Fig. 22.4). The pavement condition deteriorates as a function of traffic load and environmental conditions. The balancing loop B1 (Maintenance Fix) depicts how the maintenance operations performed by road agencies bring the road condition towards desired conditions by reducing the road area under distress. On the other hand, the reinforcing loop R1 (Accelerated Deterioration) depicts the effect of a budget shortfall on delaying maintenance and the further deterioration of pavement conditions. This initial qualitative representation of the deterioration and maintenance dynamics served as the input to the physical simulation model. For details of the simulation model refer to Fallah-Fini et al. (2010, 2013b).

The conceptualization of the dynamic evolution of road condition over time expands the dynamic representation in network DEA introduced by Färe et al. (2007). We assume that part of the highway network at period t is affected by a set of deterioration factors such as climate conditions, traffic load, etc. Based on the condition of the road, appropriate maintenance operations are performed and the road evolves to a new condition at the end of period t. The new road condition is used as an input at the start of period $t + 1$ when the road section goes under a similar transformation process. This means that the maintenance treatments during period t affect the road condition at the end of period t which is the starting point for period $t + 1$. Thus, the required maintenance operations during period $t + 1$ (and consequently the road condition at the end of period $t + 1$) depend on the maintenance operations/inputs that have been performed in a stream of previous periods.

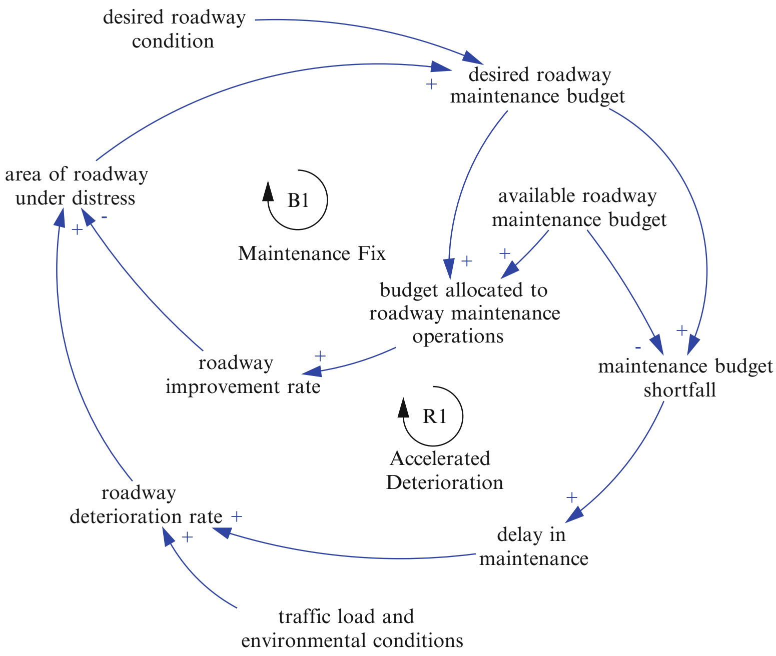

Fig. 22.4 The highway deterioration and maintenance causal loop diagram (Adopted from Fallah-Fini et al. 2010)

In such a setting, any "static" network DEA efficiency measurement framework that ignores the inter-temporal effects of inputs and managerial decisions for future streams of outputs (i.e., future road conditions) is likely to be unrealistic. The premise of this research is that successful evaluation and improvement of the performance of road maintenance practices requires a long-term perspective that takes into account the dynamics of road deterioration and maintenance.

The pavement engineering literature was studied to understand and capture the physics of the pavement deterioration (Huang 2004). Within the System Dynamics (SD) framework (Sterman 2000), the physically based dynamics were investigated in conjunction with macro-level maintenance operations. This combination allowed for constructing a simulation model that is grounded in the physics of road operations (i.e., the pavement distress generation and propagation, the effects of aging, the effect of deferred maintenance), that considers environmental conditions (the load in terms of vehicles and climate conditions) and material delays, that incorporates managerial factors (i.e., budget constraints, priorities in terms of the type of maintenance action (preventive, corrective and restorative), the thresholds associated with each type of maintenance and the actual amount of funds allocated to conduct maintenance for each road section). When executing the simulation model one can observe an adjustment path of the road condition to a new condition at the end of the simulation that is affected by the physics of deterioration, environmental conditions (traffic demand and climate conditions) and maintenance policies.

In defining and measuring system efficiency, we compared the actual road condition adjustment path (change in the state of the system) to a benchmark that represents the expected road condition adjustment path under an optimal budget allocation strategy over time. This concept is an augmentation of the output oriented concept of efficiency. To find the benchmark, we introduced a payoff representation that is a function of the state of the system at time t. For highway maintenance, the main objectives of the road authorities are to improve the condition of the highway network and maximize drivers' utilities while minimizing the costs. Thus, as an example, the payoff representation could be defined as the drivers' utilities at any point of time as a function of the condition of the road network state minus the maintenance costs. Then, starting from an arbitrary state at time t_0, the infinite horizon optimal adjustment path for the road condition can be constructed by following the optimal maintenance decisions obtained from solving an optimization problem (Fallah-Fini et al. 2013b) that maximizes driver utilities.

22.4 Conclusions and Future Research

The two examples presented in this chapter suggest that we have only scratched the surface in terms of obtaining viable network efficiency representations of engineering systems. The challenges and opportunities summarized in Sect. 22.1 remain. More specifically, micro performance representations of systems as a function of implementing the network DEA approach are opening the production "black box". In so doing, the identification of important processes that impact system performance are studied. This allows for an expanded exploration of the determinants of efficiency performance both within and between nodes and processes that are fundamental for the network DEA approach. In this sense, there is an opportunity to contribute to theory by experimentally discovering determinants of efficiency performance for a number of systems and applications.

Furthermore, we still have a limited understanding of how the structure of the efficiency network relates to which nodes and determinants of efficiency performance are important. In the case of the DSRS, the computational approach (radial versus slacks based efficiency determination) suggested that different nodes are important (i.e. the agency's versus the traveler's). This does not assist decision makers to arrive at consistent performance improvement interventions.

In terms of understanding and measuring dynamic efficiency (Fallah-Fini et al. 2013a) of engineering systems, there are potentially two distinct directions. The first simply extends network DEA formulations to include time (see for example, Tone and Tsutsui 2013). An alternative approach is to model the system's dynamic behavior explicitly (for example, using either system dynamics (Vaneman and Triantis 2007) or agent based modeling (Dougherty et al. 2013)) and then include efficiency concepts as a way to assess system performance. As suggested by the highway maintenance example of Sect. 22.3, one can view both directions as complementary since they address alternative representations of dynamics and efficiency measurement.

As argued in Sect. 22.1, engineering systems are not designed, built and operated in a vacuum. There are organizations and design teams that are tasked to do so by exchanging important information and making decisions. This suggests that we need a deeper appreciation and the integration of the social/behavioral and information sciences in our efficiency analyses and thinking. While the efficiency literature relies primarily on economic and operations research thinking it is the contention of the author that understanding of efficiency performance will be incomplete without the input from the social and behavioral sciences (sociology, psychology, cognitive sciences, decision sciences, etc.) computer science (cyber physical systems), and engineering (control systems, environmental engineering, electrical engineering, structural engineering, etc.). This suggests an even expanded inter-disciplinary approach to efficiency measurement. Network representations such as network DEA offer a viable vehicle for realizing this inter-disciplinary perspective. However, all of this is contingent on consistently revisiting the axiomatic framework on which efficiency analysis is based on.

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