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Resources for Sustainable Economic Development: A Framework for Evaluating Infrastructure System Alternatives

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Abstract: We are at an early stage of a massive global build-up of public infrastructure. Long lifetimes, high money costs and resource-intensity, and the rippling effects of the built environment on all aspects of daily life call for informed public conversation about the available choices before they become a *fait accompli*. Substantial literatures address the phenomenon in terms of economic development, resource scarcities, impacts on climate and ecosystems, technological options, human rights, funding sources, system governance, inter-governmental agreements. This paper describes a modeling framework that integrates some of these concerns about the differential impacts of large-scale centralized infrastructure systems, smaller-scale decentralized systems, and hybrid combinations. Building on existing collaborations between economists and engineers, the paper proposes a case-study research strategy to organize new types of technical information to supplement existing databases of the world economy. The paper describes needed model extensions to estimate money costs, resource requirements, resource recovery potential, and jobs and livelihoods under alternative infrastructure assumptions. The agenda supports the Sustainable Development Goals (SDGs) by identifying and evaluating globally relevant alternative infrastructure designs. The SDG process, in turn, provides both the global network and the concern to promote local development to which the proposed effort aims to contribute.

Keywords: public infrastructure; sustainable development; case-study research strategy; scenario analysis; world input-output model; dynamic input-output model

1. Introduction

Most of the natural resources appropriated for human purposes are incorporated in built structures, which by definition have long lifetimes in use and often also long lead times from concept to completion. The duration from design to abandonment often lasts the better part of a century, a substantial commitment that calls for a comprehensive, upfront examination of the alternatives before they are put in place. The global mass of materials embodied in built capital, mainly metals and non-metallic minerals, is estimated to have increased 23 times over the last century, and still today recycling accounts for only about 12% of the corresponding resource inflows [1]. Observers anticipate that this expansion of built capital will intensify in the 21st century, especially in the form of mega-scale constructions [2].

Mega-scale projects, often one-of-a-kind, are under construction or in the planning stage throughout the developing world. These include the massive Grand Inga dam complex on the Congo River, multiple structures on the Blue Nile in Ethiopia and the Mekong in Southeast Asia, and the Belo Monte dam on a tributary of the Amazon River. China's mega-projects include the partly completed South-to-North Water Transfer Project and the New Silk Road project, consisting of transport networks over land and by sea across Asia, along the coast of North Africa, and extending into Europe. Libya's Great Man-Made River draws upon a fossil aquifer to comprise the world's most ambitious irrigation project. Global spending on the mega-projects alone is estimated at $6–9 trillion annually, as we enter what Flyvbjerg calls the era of trillion dollar projects [3]. The goals of these and many other development projects, including those of the U.N. Sustainable Development Goals, are to provide basic services to expanding populations in urban agglomerations of unprecedented population sizes and densities as well as to the several billion people who will still be located in rural areas.

Repair and modernization, if not outright replacement, of aging public infrastructure in developed countries are also on the agenda. The American Society of Civil Engineers rates the condition of infrastructure in the U.S. as poor, estimating required investment over the next ten years at $4.6 trillion [4]. Mirza and Shafqat Ali [5] review estimates of the global cost and conclude that it could come to over $100 trillion.

These global agendas for public infrastructure can be expected to generate fierce competition both for material resources and for funding. New design concepts and an institutional commitment to systematic maintenance of infrastructure throughout its life cycle may be able to alleviate these pressures while also providing other kinds of benefits. The advantages of smaller scale, increased efficiency, and management of demand over increase in supply were spelled out decades ago by Lovins in the case of energy [6] and Gleick for water [7]. Despite language today about the importance of this "soft path", some analysts are concerned that "big infrastructure" is prevailing on the ground [8] and that the debt accumulated for this purpose by developing countries could lead to a serious debt crisis [9].

Smaller-scale decentralized systems can serve as alternatives to large and highly centralized ones or as components of multi-scale distributed, or hybrid, systems. A number of claims have been made for the advantages of decentralized and hybrid systems: that they can be better matched to a community's unique attributes and its needs and preferences, are less disruptive to community culture and physical landscape, foster local buy-in and local governance, provide local jobs including opportunities for entrepreneurship, are more easily upgraded over time in a modular fashion, and are more resilient to natural and man-made disasters. It has also been argued that distributed systems are generally less capital-intensive, less costly and more likely to rely on local resources, in particular renewable ones, rather than competing in global resource markets. However, Sapkota et al. [10] point out that these system designs are relatively new and more evidence is needed about costs, maintenance, public health, interface with the centralized systems, and governance. Farrelly and Brown [11] call for on the ground experimentation with alternative distributed technologies and practices. They point out that existing experiments are largely carried out in isolation from each other and require "an explicit coordinative mechanism" to inform action.

This paper proposes an analytic modeling framework, based around a highly structured database of concrete technological designs, to serve as one sort of coordinating mechanism by making it possible to compare and contrast different options. The framework requires supplementing existing economic databases of the world economy with a new kind of information that describes the infrastructure alternatives from an engineering perspective. One challenge is that the setting for every implementation of the same type of infrastructure is essentially unique. The ability to generalize about a system's requirements and impacts, and systematize information about the kinds of settings to which it is, and is not, suited is vital for the eventual transferability of project designs that are successful in some settings to other locations. By generalizing from bottom-up case studies, one can create a new information source for analyses using top-down models of individual economies, and of the world economy. The results of the top-down analyses, in turn, provide input for reconsidering the prospects on the ground. The motivation for building this database is described is described by Duchin [12].

Subjecting alternative infrastructure designs for specific geographic settings to model-based analysis in the context of the global economy constitutes a new departure that requires significant extensions to and integration of existing models. One of the main modeling challenges, addressed in the paper, is recognizing that sectors have different production periods, corresponding in particular to long construction times for infrastructure projects, within a dynamic framework where a sector's production capacity is increased only when the project it initiated is completed. Different points in the life cycle of the infrastructure also need to be distinguished for maintenance. These representations represent a substantial extension of existing dynamic models.

The remainder of the paper describes this research agenda. Section 2 is a review of case studies of decentralized and hybrid infrastructure systems appearing in the technical literature. These particular studies have been selected because they situate the technological attributes within a broader social and economic framework, and they draw conclusions about the relevance of the study for other geographic settings. Section 3 describes a case-study research strategy for building a database about infrastructure requirements. The economic modeling framework is described in Section 4. It sets out to integrate existing four input-output models that have been applied for empirical studies of sustainable development: a model of the world economy, a model with a sector-level choice among alternative technologies, a model of material recovery for potential reuse in the same or other applications, and a dynamic model. The resulting model is intended to make operational the new representation of infrastructure while also integrating the other capabilities. The final section of the paper discusses the proposed agenda as a whole and situates it in relation to the inter-governmental agreement on Sustainable Development Goals.

2. Literature Review of Infrastructure Case Studies

As Moser has pointed out [13], infrastructure has such a decisive influence on everyday life that decisions about what constitute priority needs, and design strategies for how to satisfy them, necessarily embody a vision of the future. The guiding ideas are to design integrated systems rather than isolated components, facilitate the interdependence among systems, deploy multi-scaled systems, design for the entire life cycle, and use modular design to enable responding to changes in societal and material environments. This section reviews several case studies that illustrate these concepts. It is followed in Section 3 by a proposed research strategy that provides a structure for case studies to facilitate generalizing from specific situations to construct a globally relevant database.

Developing concrete infrastructure designs must satisfy functional requirements while also accommodating the particularities of each individual setting. Buchanan [14] describes design as a discipline of "integrative thinking" to solve "wicked problems," meaning problems that are complex, have no single best outcome, and are too often dealt with in a fragmentary way by specialists working in isolation from each other. He calls for collaboration among individuals of diverse backgrounds and interests, who rethink both the problem and possible solutions collectively and—importantly—are keen to understand what is relevant and useful in each other's contributions. The design of infrastructure qualifies as a wicked problem, and the rest of this section describes several efforts to come up with solutions.

The need to develop new strategies for civil infrastructures is addressed by H. Brown [15], who illustrates such strategies in two subsequent volumes devoted to industrialized societies [16] and developing countries [17], respectively. The author identifies five objectives relevant for all types of infrastructure and illustrates each by about a dozen projects that have actually been realized in recent or historic times in locations around the globe. These establish the feasibility of achieving the goals, but the descriptions are very brief, and the cases differ in functional goals as well as scope. More structure and detail are needed to assemble a database. In a similar effort, Bell [18] describes concrete instances of decentralization in different settings and from multiple points of view and assesses their advantages and disadvantages. The descriptions exhibit a variety of arrangements but there are not enough cases, nor enough information about individual cases, to characterize the different approaches.

Daigger [19] points out that urban water systems in place in industrialized countries were developed in times when water was abundant, energy inexpensive, and water treatment technologies not yet established. Multi-purpose systems evolved not by design but by sequential addition of single-purpose components, one at a time, and largely operated independently. Daigger describes how centralized systems with single-purpose components could transition to integrated systems including distributed components. One such component is the separation of distinct wastewater streams generated at a particular site and their on-site treatment for reuse, a generalized concept that can be customized for diverse situations and is revisited below.

Lorente et al. [20] study a hypothetical distributed solar energy system with two functions: it produces and distributes power over a given populated region, and it services plants that desalinate water for distribution throughout the same area. The authors show that both types of plants exhibit energy economies of scale in production and that, also in both cases, these advantages are offset by energy losses in distribution with increases in the total area serviced. However, the net impact on energy requirements is different in the cases of power delivery and water delivery. The authors arrive at general guidelines for the spatial layout for an energy-efficient system as demand grows for both power and fresh water. The capacity of both types of plants will grow (due to economies of scale), but the number of desalination plants per power plant will increase as each one serves a smaller territory (because of the relatively greater loss from longer distribution distances for water). These calculations do not take account of site-specific issues (like the amount of solar radiation and sources of available water), nor do they estimate economic costs. However, the conclusion illustrates a general principle for the integration of two or more distributed systems: that changes in the spatial layout of a system should be anticipated with the growth in demand.

Moving to quantitative analyses, the most common modeling approach for choosing among alternative design options is a formal mathematical optimization of a selected criterion subject to constraints. Leung Pah Hang et al. [21] study the decision-making process for choosing among alternative designs for integrated local food, energy, and water systems, by comparing the results of two approaches: presenting decision makers with the numerical results of a formal optimization procedure or engaging them in what the authors call an "insight-based" experience. In the latter case the decision makers obtain and discuss numerical results generated at intermediate stages of the analysis, which proceeds incrementally and takes their feedback into account. Both approaches lead to essentially the same qualitative outcomes. The formal objective function has a slightly improved numerical value in the former case, but the authors report that the latter provides decision-makers with a better understanding of the implications of the different alternatives.

C. Brown et al. [22] propose a new agenda to the community of water resources systems analysts, which traditionally has seen its role as providing input to local water managers. The authors argue that, since these local problems are both global in impacts and common to many situations, the community's work can have a much greater impact if the outcomes of individual investigations are generalized to other sites. They believe that this outcome requires two innovations: strengthening their field's scientific foundation (in ways that are not specified) and broadening the scope of inquiry through multidisciplinary collaborations that address socioeconomic challenges along with biogeochemical ones. While they still envision methods based on formal optimization, they endorse focusing on options for the future, not just the past and present, and, like [21], "softening" the formal models to encourage more interaction with stakeholders. This presumably means making effective use of qualitative information as well as a formal model in reaching conclusions.

In recent years there has been a notable increase in case study research in the field of construction engineering and management. However, most instances are essentially descriptive with only a minority attempting to provide a basis for generalizing from each set of results. Taylor et al. [23] offer a checklist to provide more structure and rigor in conducting case studies with the goal of deriving what they call *theoretical* generalizations. The authors conclude that the necessary first step is to make very clear both the research question that the case study is meant to illuminate and the unit of analysis, which is often not easy to define since cases are typically unique and site-specific. As pointed out decades ago by Yin [24], frequently "the boundaries between phenomenon and context are not clearly evident". This is indeed the central challenge in generalizing from specific cases.

Newcomer et al. [25] provide a case study about the feasibility of re-using domestic grey water in rural areas of Malawi. They interview local households about acceptance of reusing wastewater and test water samples for contamination in a community that belongs to a Water Users Association that is supported by a non-governmental organization (NGO). The authors find that grey water quality is site-specific and highly variable: they recommend intensive testing and on-site treatment before reuse for any purpose, as many kinds of contaminants were discovered. They also recommend installing meters, as they observe considerable waste of running water. The recovered water is used for producing food, flushing toilets, and making bricks, the last of which is a common source of income in this particular setting. They state that their recommendations are relevant for the rest of rural northern Malawi and other water-stressed areas of sub-Saharan Africa, but no specific reasons are offered to support this claim.

The Brazilian government provides housing that is equipped for water and sanitation services in low-income areas, in particular for the city of Florianopolos in southern Brazil. Vieira and Ghisi [26] compare the energy requirements associated with rainwater harvesting and grey water reclamation to those for providing centralized water and sewage services in Florianopolos. The volume of rainwater available as a portion of total household demand for water exceeds that of grey water in this setting, but both sources combined would not be adequate to satisfy current household requirements without complementary input from the centralized facility. The authors conclude that the storage, pumping and treatment of rainwater is more energy-intensive per cubic meter of water for onsite provision to the average individual dwelling than by centralized provision due to the economies of scale achievable in the latter case. However, grey water reclamation, with its use limited to flushing toilets, was found to be more energy-efficient than either rainwater or centralized treatment in Florianopolis, where treatment can rely on percolation through constructed wetlands and septic tanks operated by gravity with no use of electric power. Since the volume of grey water is not able to satisfy the total demand for the disposition of sewage, its advantage is measured by the reduction in demand that would otherwise be placed on the centralized facilities. The comparison undertaken in this case study is surely relevant to other sites. However, both more cases and a more systematic way of describing the special contextual features—such as current water use, precipitation pattern, availability of land suitable for sewage disposal—would be needed to generalize findings from case studies examining similar technical options in other settings.

Shirley and Kammen [27] report that the Malaysian government promoted small, distributed, renewable energy projects in the 2000s, but for reasons that are not explained the program never took off. The authors attempt to redirect attention, in Malaysia and elsewhere, to distributed technologies: their paper examines the prospects for adding decentralized infrastructure using renewable sources into the planned mix of large-scale, centralized energy projects in the state of Sarawak in Malaysian Borneo. They use a commercial software package to identify cost-minimizing technologies to expand capacity beyond that which is already committed. The authors conclude that the small-scale renewable options of run-of-river hydropower schemes, converting local biomass wastes (palm oil) to energy, or solar photovoltaic installations, would come on line under the assumption of sufficiently high rates of growth in demand, but even then only with government subsidies. They also conclude that the official projections of the future power demand for Sarawak far exceed what is realistic for the needs of the local population. These growth rates reflect the government's plan to attract heavy industry to the region without the opportunity for local consideration of alternative development strategies.

Shirley and Kammen claim that their findings about alternatives to large-scale energy infrastructure for Sarawak are applicable to other developing countries as well, not only in the Lower Mekong River Basin but also across Africa and Latin America [27]. However, this claim is hard to justify, as the study does not attempt a systematic distinction among the attributes of the technological alternatives or a characterization of the unique attributes of the site. In fact, even the assumptions behind the conclusions for Sarawak are not clear. A great deal of detailed data has been assembled, but its purpose is to satisfy the requirements of the model utilized. An important advantage of customizing research models to specific questions over using off-the shelf models is that the former allows selecting the variables most important for the questions being addressed and ignoring a great deal of detail that the researcher considers less relevant to the inquiry.

The studies reviewed are mainly from engineering journals or journals focused exclusively on water or energy issues, and all evaluate the choice of decentralized or hybrid systems, mainly for energy or water. However, each study defines a different system of interest as well as a different setting. In the absence of a cumulative effort, only the most general conclusions can be reached on the basis of comparing and contrasting the study outcomes. There need to be a taxonomy of the systems of interest, technical description for each category of system, and a profile for each setting in terms at least of relevant resource endowments and socioeconomic characteristics. Then a series of case studies can be carried out for the potential adoption of specific types of systems in regions with selected profiles. The added structure facilitates reaching generalizable conclusions.

3. A Case Study Research Strategy for Constructing a Database

All models of an economy that distinguish the requirements and the impacts of distinct sectors of the economy make use of input-output databases. However, it is a distinctive feature of input-output models, even in their simplest forms, that they represent sectors in terms of their technology-based inter-sectoral dependencies. The input-output models of broadest conceptual scope, the subject of the next section, provide substantially more detailed representations of technologies and technological choices, making direct use of engineering information in physical units. This section addresses the use of case studies as a source for building the necessary database.

At the center of an input-output database is the input-output table, which has historically been compiled in money values by national statistical offices from census and survey data for a given past year. The table is structured around a standardized classification of sectors, and it quantifies for each sector the amount of each input required to produce its characteristic output in that year. This method works reasonably well for most goods and services, but it cannot accommodate a description of infrastructure requirements without several innovations. The first new requirement is a taxonomy of the sectors involved in the provision of infrastructure. Most input-output tables include only a single construction sector and quantify the amount paid for each of its inputs, and the amount received for its deliveries to each purchasing sector, in the year in question. This construction sector needs to be substantially disaggregated to reflect the types of construction of interest, for example dams, power plants and distribution networks, or rainwater harvesting and greywater reuse systems. Second, a typical infrastructure project cannot be completed in the standard production period of one year, so its inputs and outputs need to be sequenced for each time interval over a suitable time period. Third, analysis of scenarios about the future requires assumptions about structures that are not yet in place. Data for representing them will need to come directly from engineering sources and not from accounting sources. This section describes an approach to extending the input-output database through the collaboration of input-output economists with industrial ecologists on case studies.

Infrastructure case studies, and generalizations derived from them, constitute a new kind of information source for informing the content of scenarios about the future. To serve this purpose, it has to be possible to deduce data describing potential options for locations lacking case studies from studies of existing installations, including experiments. That outcome requires that the case-study strategy use taxonomies to organize the available material. Johansson et al. [28] describe one relevant use of taxonomies. They estimate that the global built environment now contains at least as much material as the remaining virgin ores and focus on the considerable potential contribution of recovering the resources embodied in built capital. However, realizing this potential requires a shift in mindset from mining the earth's crust to mining the technosphere, and from managing resource-related wastes to managing stocks of built capital throughout their life cycles. Making this shift requires a classification of the resource reservoirs in the technosphere. I conclude this section by proposing two complementary taxonomies to distinguish among alternatives for any given infrastructure service outcomes and among different spatial locations, which might be used separately or jointly to separate the phenomenon of interest, namely the type of infrastructure design, from the context in which it has been implemented.

The objective of a case-study research strategy is to help identify the requirements and the consequences of providing alternative technological systems for delivering similar but not necessarily identical functionalities to one or more similar—but never identical—communities. The taxonomies are intended to characterize the systems and the communities as a basis for determining the potential suitability of a particular system in a given setting. The taxonomies also facilitate identifying additional kinds of communities and technologies for which case studies are needed for broadening the coverage, to enable drawing conclusions for a wider set of cases. The taxonomies themselves are quite simple; their value lies in providing a structured methodology for reaching generalized conclusions. As Yin [24] points out, one generalizes from cases to a theory, and it is the theory that is then applied to new cases.

The first set of properties for classifying four broadly different types of communities would distinguish urbanized areas, urban-rural transition areas, rural towns, and open countryside and for each community its surface area, population, and population density as well as the mix of local skills, present sources of livelihoods and some measure of income distribution. Existing infrastructure and infrastructure services, if any, for the system under study need to be described. Other relevant variables are the water sources, and their quantity and quality, as well as energy sources, main climatic features and relevant landscape features. For an existing water system, one would specify treatment of intake water, distribution capacity, fate of wastewater streams except sewage, fate of sewage, and treatment of wastewater streams and subsequent reuse. For an existing energy system, energy sources in use, electric power sources and quantities, choice and scale of generation technologies, and extent and features of the distribution grid, if any, need to be described.

A classification for infrastructure systems would be refined in the course of the case study work, as would alternative approaches for achieving their objectives. The case studies would also be the source of information to quantify the time-phased input structures for alternative options and identify the types of communities for which different alternatives are relevant. These kinds of case studies must be a vital part of the agenda for formulating and evaluating sustainable development scenarios. Duchin [12] describes the advantage to conducting individual case studies with the expectation that the results can be useful to inform other case studies in a cumulative fashion and as input to top-down models; in return, conclusions from the formal models, like those described in the next section, can explicitly indicate results that are useful for the formulation of subsequent bottom-up studies.

4. The Economic Modeling Framework

Several contemporary input-output models represent economic sectors in terms of their production technologies, focusing on sector-level interdependence, and they have mathematically complementary representations in mixed physical units and in associated money costs and prices. These features explain the already substantial engagement of engineers with input-output models and databases, a practice that can bring unique and unprecedentedly concrete representations of technology into economic analysis. However, to date only the most basic input-output model has been used in the engineering literature. Input-output models include a dynamic model of investment in built capital to expand production capacities, the waste input-output model representing resource recovery for reuse, and a global model with world regions linked by international trade based on comparative advantage. These and other conceptual extensions are formalized in mathematical models that have been applied in a variety of empirical studies. The objective here is to achieve their deeper integration while also benefitting from both the multi-faceted technological knowledge base and the techniques of life cycle analysis and material flow analysis, which are central to Industrial Ecology.

Wassily Leontief launched Input-Output Economics nearly a century ago with two pioneering articles [29,30], which built on Quesnay's *Tableau Economique* from the 18th century and the general interdependence concept of Leon Walras a century later. Leontief made major theoretical and methodological contributions to economics, but he most stands out among his contemporaries for his emphasis on data compilation for empirical analysis over abstract theorizing. From the beginning, he systematically sought out collaborations with engineers, but that did not prove easy to organize.

Levine and Romanoff, whose work is discussed below, also explicitly set out several decades ago to integrate economic and engineering considerations of production and construction.

The field of Industrial Ecology is about thirty years old, has its roots in engineering, and is committed to "finding innovative solutions to complicated environmental problems" (https://is4ie.org/). One analytic subfield is life-cycle assessment (LCA), which systematically compiles databases of environmental impacts at all stages of production and use of individual products or production processes. Another is material flow analysis (MFA) of resource stocks and flows with an emphasis on their distribution throughout an economy. In recent years a community of researchers has emerged who utilize the concepts, data, and techniques of both input-output economics and Industrial Ecology to address a wide range of questions related to sustainable development. Some examples of this confluence are the environmentally-extended input-output databases [31] and a large and growing number of empirical studies using hybrid methods. Pauliuk and colleagues [32,33] call for the integration of this range of component models from an Industrial Ecology perspective, and they amply demonstrate the objectives shared with economists. The ideas laid out in this paper are meant to reinforce other efforts for deepening the integration between Input-Output Economics and Industrial Ecology.

The intention is to situate a model of the world economy based on comparative advantage within a dynamic framework, which in addition is conceptually extended to permit a more realistic representation of infrastructure than has been previously attempted.

4.1. Comparative Advantage

The theory of comparative advantage holds that each region will tend to specialize in producing those goods and services for which it is the relatively lowest-cost producer and export the excess over domestic requirements. The amount produced is limited by the region's resource endowments: once a low-cost region exhausts a critical resource, a higher-cost producer needs to supplement the former's output, and so on for progressively higher-cost producers, until world demand is satisfied. The highest-cost producer sets the world price, and the lower-cost producers earn an extra profit, or rent, on the scarce resources they have exhausted.

Comparative advantage is highly valued as a theory explaining international trade flows. In fact, it is far broader than that, in that it explains the interdependence of the quantity of each good produced in every region, the price of the good, and the earnings of all factors of production, namely workers' wages and returns on built capital as well as payments, including scarcity rents, for land, water, and other resources. A generalized interpretation of this theory is embodied in the World Trade Model (WTM) [34], a constrained optimization model that situates the standard one-region input-output model within the global context. In this model, unlike the case for other input-output models, prices and quantities are fully interdependent. The global context is needed for analyzing the implications of alternative infrastructure designs at the implementation scales that are anticipated, in particular because of trade in resources and in engineering and construction services and the impacts of future resource recovery from aging infrastructure on economies depending on extraction and export of virgin materials.

The same logic of comparative advantage can be applied simultaneously in individual regions that possess multiple technological options for production in one or more sectors. This representation is called the Rectangular Choice-of-Technology (RCOT) model [35]. This capability allows for choices among infrastructure alternatives based on cost comparisons, or based on other criteria such as minimizing carbon emissions, or subject to constraints set by natural limits or by government policies. When the RCOT logic is included within the WTM [36], the resulting framework provides a realistically broad set of technology choices, namely among different options within each region as well as across all regions. The WTM and the RCOT model have been implemented in a variety of empirical inquiries regarding specific aspects of sustainable development [37–46].

4.2. Economic Dynamics

Baynes and Müller [47] point out that many model-based studies addressing climate-related challenges focus exclusively on the use of energy and the associated emissions, overlooking the distinctive importance of built infrastructure, the resources on which it depends, and the energy and material implications of prospects for recovery of these resources. The authors call the failure to explicitly study infrastructure the "blind spot" in climate change modeling. They emphasize the need to represent infrastructure as economically significant material stocks, not only money values of investment flows, and argue that sectoral level analysis must capture inter-temporal interactions among sectors. It is precisely by these capabilities that the dynamic input-output model extends the more familiar static input-output model. However, representing these stocks in a way that is empirically useful poses both conceptual and empirical challenges that are addressed below.

Duchin and Szyld [48] developed a dynamic model of the U.S. economy that includes one particularly important new feature: explicitly allowing a sector to use less than its full production capacity if its output falls or if it has over-invested in expansion. Leontief and Duchin used this dynamic model to analyze the future impact of various forms of automation on jobs in the U.S. [49], the application for which the model was expressly developed. The dynamic scenario analysis required building a database specifying changes not only in the input structures of the producing sectors but also in their requirements for expanding their capital stocks over a period of four decades. There are two main ways that this dynamic model needs to be refined for the purposes described in this paper. Most importantly, the data describing inputs to the capital stock need to be substantially improved, starting from the conceptual definition and organization of the information requirements. They need to come from technical sources, not monetized accounting data.

Sectors that provide diverse engineering and construction services for infrastructure and for durable goods need to be represented in much greater technical and temporal detail than is now the practice in any existing databases about stocks and flows of built capital. The RCOT model makes it possible to provide sectors with alternative production options, with choices among them depending upon adequacy of resource endowments and available funds, among other constraints. However, data describing relevant alternatives remain limited. Money outlays need (on average, globally and over time) to be matched by incomes earned. Thus there will be competition among would-be infrastructure projects, in fact among all investment projects, and between investment and public and private consumption. Competition over resources will influence the choices among alternative technologies. One consequence will be a strong incentive to recover resources for reuse, systematically and on a large scale. Such a modeling framework can provide estimates of how much infrastructure could actually be put in place, globally and regionally. It is also a high priority to anticipate future demand for specific key resources in comparison with their geologic abundances.

4.3. Infrastructure Construction and Material Recovery

A standard input-output table usually contains only one construction sector, and most of that sector's output takes the form of final deliveries, largely to "private investment" and "government consumption and investment". Clearly multiple construction sectors need to be distinguished, and the demand for construction projects needs to be directly associated with increased capacity to deliver services such as electric power or water, the purposes of infrastructure investment (e.g., a power grid or a dam) and, more generally, with the investing entities like a water or power utility. Since these challenges can be treated as issues of data disaggregation, they are covered by the discussion of the last section on data compilation.

However, there is one related issue that requires a conceptual advance in the model. Virtually all input-output databases and empirical studies are concerned with the production, consumption, and trade of goods and services. A dynamic analysis requires broadening this scope to include structures along with goods and services. A distinctive property of structures is that they often require more than one time period for their construction—as do some durable goods, like customized wind turbines. Romanoff and Levine [50] introduced the Sequential Interindustry Model (SIM) with the concept of an investment "project" and the associated "project schedule" [51], designating structures and associated durable equipment to be completed at different points in the schedule. They establish a production period and then allow a production activity to require any number of production periods. The model of Duchin and Szyld does the same. But there are two fundamental differences between the models. First, Romanoff and Levine distinguish and accommodate two different reasons for requiring more than a standard production period: either the sector is *responding* to demand from elsewhere in the system and needs more than a single period to satisfy it, or else the sector is *anticipating* the need for that production and places an order for it in advance of being able to use it (The model of Romanoff and Levine, however, deals only with investment flows and not with capital stocks). The dynamic model of Duchin and Szyld allows only for the anticipatory motive. This mechanism of allowing any sector to use more than one time period to deliver its output provides the flexibility required to treat structures as an output type produced by some construction sector. It also allows realistic time frames for producing specific types of durable goods, like customized wind turbines. A construction sector building a mega-sized dam will require multiple production periods to produce its output (the dam) in response to demand rather than to increase its own production capacity in the future. This is a feature that must be incorporated into a dynamic input-output model for addressing the questions posed in this paper.

At the end of useful life of infrastructure and durable goods, the embodied resources can be recovered for reuse, according to a plan established at the outset of the project or as a scenario assumption. Nakamura and Kondo [52,53] have contributed a model for resource recovery, the Waste Input-Output (WIO) model, that uses the input-output framework as a bridge linking material flow analysis and life-cycle events. The WIO model has been applied in a number of empirical studies [54–61] and is used by both economists and engineers. The existing WIO model makes use of the one-region, static input-output framework, but efforts are in place to situate it in a global setting, or a dynamic one, or both: see [32,33,62,63].

Industrial Ecology includes a large body of work on material flow analysis, including both stock-flow models and a substantial compilation of data about in-ground and technospheric stocks, especially flows of numerous metals through the economy. Müller et al. [64] provide a review of dynamic MFA models. There are obvious advantages to integrating the resource stock-flow relations within a dynamic input-output model of an entire economy with endogenous stock-flow relations for built capital. Springer [65] realized an important conceptual advance in this direction, which he applied to assess future global availability and world price for phosphate rock using the WTM/RCOT framework. He disaggregates region-specific reserves and resources by estimated ore grade; next he provides alternative technologies suitable for extracting each grade. With expanded demand for phosphate rock, the disaggregation by grade suggests substantial increases in price as production shifts to regions with lower grade deposits that require higher-cost technologies. Springer's study demonstrates the kinds of questions that can be addressed with more refined quantitative descriptions of resource stocks that distinguish technologies needed for extracting and refining them.

The extension of the dynamic input-output model of Duchin and Szyld [48], incorporating the capabilities discussed above, is in progress.

4.4. Model and Data

An empirical analysis requires that the model be based on defensible and transparent logic and be accompanied by a compatibly structured database with documented empirical content. There are now several input-output databases of the global economy, including supplementary information about resource use and environmental impacts, of which Owen [31] provides a comparison. These databases are widely used, with many kinds of models. However, additional types of information are needed to move from statics to dynamics, namely the time-phased input requirements for producing structures and durable goods, as described earlier. The challenge is one of defining the information requirements and how to systematize them; the source will necessarily be engineering data, not accounting data.

The economic database for a dynamic input-output model includes a time-ordered sequence of parameter matrices that quantify infrastructure input requirements. The relevant definition of a matrix entry is units of input required per unit increase in production capacity. Unfortunately, there are no existing economic databases describing capital stock requirements that come close to providing adequate technical content to associate them with resource stocks and flows. In building their database for the dynamic model thirty years ago, Leontief and Duchin [49] did not have active collaborative relationships for developing engineering information. Today that prospect feels much nearer at hand.

The need for new sorts of information content has been indicated throughout the paper. They start from the identification of relevant technology system designs and their analysis emerging from case study research. The case studies would also provide information about which options might be relevant for different locations. Scenarios can then be formulated that specify particular combinations of system options for different regions.

The database requires the time-phased matrices of construction and maintenance schedules for the different categories of infrastructure and for durable equipment. These data should be quantified in the units that are natural for the researchers producing them, which generally means physical measures in mixed units. Consequently, mixed units need to be used consistently throughout the database. Today's global input-output databases include abundant supplementary data in physical units, but the basic input-output information is typically still expressed in money values only. Attention will need to be paid to the choices of units as the scope of the coverage is expanded from goods and services to include structures and selected durable goods. Accounting data are no longer an adequate source as we move to studying scenarios about prospective technologies for the future, and little information is available about the global distribution of resource deposits by quality and accessibility. Engineering expertise is needed to describe infrastructure projects, in units that the technical specialists use for their own analytic purposes: the input-output framework can in principle work with any set of units. The database also needs to include estimates of the region-specific endowments of relevant resources distinguished by grade of deposit and technologies for exploiting the different grades.

The availability of several input-output databases covering the world economy is relatively recent, and there is no shortage of next challenges to take on. Likewise for the models, some model integration and extensions have already been achieved, and other efforts are in progress. A sustained effort will be needed to meet the data and modeling objectives. Some early explorations using illustrative numerical data that demonstrate what can be learned by doing so would help motivate the substantial data compilation and modeling efforts.

5. Discussion and Next Steps

This paper is concerned with achieving the two goals associated with sustainable development: protecting the natural systems that support life on the planet and redressing the vast material inequalities responsible for human suffering and political instability. The paper identifies decisions regarding public infrastructure as decisive for achieving both goals and describes a systematic effort to evaluate the promise of smaller-scale, distributed infrastructure in this era of mega-sized, centrally controlled infrastructure projects. Infrastructure alone will not suffice, but making the wrong infrastructure choices will aggravate both problems for a very long time to come. The collaboration between the research communities of engineers and economists is in a position to develop and evaluate a variety of options as a basis for action.

The paper makes the case for building an analytic capability on the existing strengths of input-output economics and Industrial Ecology. It proposes a case-study research strategy for developing the content about alternative infrastructure systems and describes the logic behind models and model extensions for the analysis of the databases to which they are applied. It is clear, however, that the agenda will require other vital components as well that have not been addressed here. Among these are social institutions to initiate the engagement of the communities that would be served by the infrastructure to be put in place.

Foremost is the question of the rights and expectations of the people whose livelihoods and lives are most directly affected by the infrastructure projects. If populations remain where they are and acquire access to safe water and sanitation services, energy, education, and health care, participating in the decision-making processes and gaining jobs and opportunities, then one can talk about economic development. A key to achieving this outcome is assuring that there are both global dialog about the options and community empowerment to be heard.

Sexsmith and McMichael [66] identify a crucial disconnect—they call it a blind spot—in the Sustainable Development Goal process: it aims its proposed targets at the heads of sovereign states, whereas the challenges we face are global in nature, and the impacts are experienced locally. International law might be the right domain to seek consensus on addressing the rights of land users in their own countries and of stateless workers. The agenda sketched in this paper can provide useful input for both global dialog and community engagement. Stafford-Smith et al. [67] call for the Sustainable Development Goals to progress from setting a list of targets to providing the kinds of inputs needed for implementation on the ground. As the first step, they see the need to strengthen various linkages among the many individual SDGs. This paper makes the case that the focus on infrastructure design can establish such connections and identifies a community of researchers who are motivated to flesh out a variety of options.

The infrastructure projects attracting attention today, with support from the World Bank, affiliated development banks, new institutions including the Asian Infrastructure Investment Bank and the New Development Bank, and an emerging global engineering and construction industry, are mega-projects. The principal concern of these actors is to improve the management of such projects, acknowledging that they are typically vastly over budget, significantly delayed, and showing lower benefits than had been projected [3]. The research communities discussed in this paper are in a position to provide designs for various combinations of smaller-scale, decentralized, and distributed systems to serve the needs of the half of the global population living in cities, the several billion more who will be joining them, and the other half of the global population who live in rural areas, whose numbers are expected to decline but only slightly. The idea is for this knowledge base of infrastructural design to be a shared resource, rather than a proprietary asset, that can be considered and implemented in many places through an active practice of global technology transfer. At the local level, this shared resource can inform communities about the kinds of local livelihoods that could be generated by putting the new infrastructure in place, and other kinds of livelihoods that would benefit from the existence of this new infrastructure. Communities can use such ideas as starting points for designing local proposals, presenting them as alternatives to plans meant to attract initiatives like plantation-scale agriculture or large-scale energy-intensive manufacturing to exploit mega-sized hydroelectric power projects. This kind of process could make a persuasive case supporting different kinds of infrastructure decisions. Such a capability would support the objectives of the Sustainable Development Goals and could help them progress from a list of targets to concrete implementation plans.

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