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Integrated analysis of commuters' energy consumption

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Abstract

There are strong interactions between energy consumption at home, in the office, and in the traffic system. For example, workers can telecommute, saving the energy at the office and in the transport system, but on the other hand increasing energy consumption at home. As an alternative measure, making working hours less flexible and thus forcing everybody to be at the workplace at the same time reduces the energy consumption of the office building. Both measures in addition have traffic congestion consequences. This paper discusses these policies based on a simple analytical model as well as based on a simulation model which includes a sophisticated simulation of the transport system.

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1. Introduction

Sustainability is a prominent topic in the public discussion. One problem is energy consumption. About 70 to 75% of the final energy in the European Union (EU) is consumed by transport, dwellings, retail facilities, and offices[1]. In this situation, *"[t]elecommuting is often cited as a promising strategy for reducing travel demand"*[2], especially in the peak hours. Mokhtarian et al.[2] further find that noncommute travel also decreases when telecommuting is implemented. Koenig et al.[3] state that not necessarily the number of trips but the travelled distance is reduced, that is, former commuters choose different locations e.g. for their leisure activities. Thus, looking at the consequences of telecommuting approaches to the traffic system seems to be necessary. However, telecommuting does not only affect the traffic system. Agarwal et al.[4] show empirically that presence at the office/workplace does directly affect the energy consumption. Haldi and Robinson[5] implement a model that shows the influence of occupants presence and behaviour. Kitou and Horvath[6] analyze that complex system, particular the consequences to emissions, based on a Monte Carlo Simulation. However, for a detailed planning a more detailed simulation seems to be necessary. As e.g. stated by Haldi and Robinson[5], for a detailed simulation of the building energy consumption a lack of occupancy data makes detailed planning impossible.

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In this work we will show a) the ability to determine consequences of telecommuting on the one hand and reduced working hour flexibility on the other hand to the traffic system and the resulting energy consumption based on the agent-based mesoscopic traffic model MATSim and b) that the model is capable of delivering information about occupants presence to building energy simulation frameworks. For this we will first give a short description of the used traffic simulation MATSim and the selected case study area, Berlin, Germany. Then we describe a simple analytical model to approximate the energy consumption. The following section then describes the methodology and results obtained with a simulation model, including a detailed traffic simulation model. The paper is concluded by a discussion and a summary.

2. Transport model and scenario

2.1. Multi-Agent Transport Simulation

The simulation approach used in this paper is based on the software tool MATSim[7,8,9]. A short introduction is given here to define the relevant nomenclature. In MATSim, each traveler of the real system is an individual virtual person, modeled as agent. The approach consists of an iterative loop that has the following important steps:

1. **Plans generation**: All agents independently generate daily *plans* that encode, among other things, their desired activities during a typical day as well as the transportation mode. Virtual persons typically have more than one plan ("plans database"). Exactly one plan per agent is selected.
2. **Traffic flow simulation**: All selected plans are simultaneously executed in a simulation of the physical system (often called "network loading"). Events are created for every action agents perform, e.g. a *LinkEnterEvent* for a vehicle or agent entering a link.
3. **Scoring**: All executed plans are scored by a *utility function*. The utility function can be personalized for every individual.
4. **Learning**: At the beginning of every iteration, some agents obtain new plans by modifying copies of existing plans. This is done by several *modules* that correspond to the choice dimensions available, e.g. time choice, route choice, and mode choice.

The repetition of the iteration cycle coupled with the plans database enables the agents to improve (learn) their plans over many iterations. The iteration cycle continues until the system has reached a relaxed state. At this point, there is no quantitative measure of when the system is "relaxed"; the cycle runs until the outcome is stable.

2.2. Scenario: Berlin - Brandenburg

We take an existing scenario for the Berlin region which has been used previously[10,11]. The network is generated from the OpenStreetMap project (OSM)[12]. The resulting network consists of approx. 24,000 links and 11,000 nodes.

The demand for the current study is derived from a so-called "BVG household survey" from 1994 (also see[13,14]). That survey contains detailed trip-diary informations of a person on the specified day. The outcome of this survey results in 57,688 persons performing 209,416 trips. This is corresponds to approximately 1% of the population in Berlin-Brandenburg. 56,160 persons of those perform home activities, 23,097 perform work activities. 23,095 build a cut set of persons performing both activity types; this set builds the investigated population group within this study. Within this group, 54% of all all trips are performed by car, 25% with pt, and 21% by other modes, mostly walk and bicycle.

To derive a basecase, the simulation was run for 1,000 iterations. Agents are allowed to replan in two dimensions, time scheduling and routing, until iteration 800; afterwards, they can only chose between existing plans. The outcome is a validated scenario which is used as base case. Validated means the agent scores do not change any more (Fig. 1c), and the simulated and real traffic counts are close to each other as shown in Fig. 1a and 1b. The counts and the road network refer to 2009/10, which means that the demand from 1994 generates plausible 2009/10 traffic patterns.
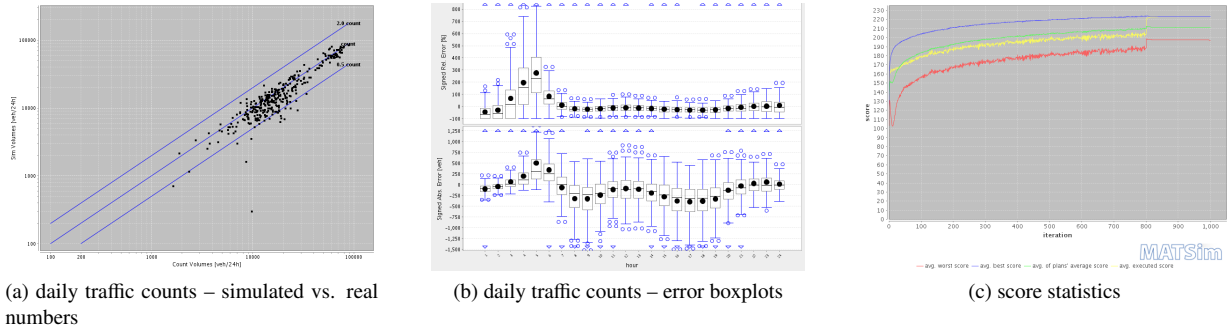
(a) daily traffic counts – simulated vs. real numbers

(b) daily traffic counts – error boxplots

(c) score statistics

Fig. 1: Berlin-Brandenburg results for the basecase after 1,000 iterations.

3. Analytical Model

As a benchmark, we first consider a "back-of-the-envelope" model for the calculation of building energy consumption, including the average commuter energy consumption.

3.1. Approach

It is assumed that offices open and close at t_s and t_e, and that core hours—where everybody needs to be present—are from t_{cs} until t_{ce}. Therefore $t_s \leq t_{cs} \leq t_{ce} \leq t_e$. For the probability $p(t)$ for a person being in the office at time t it is assumed that all persons are at work within the core hours. For the times between t_s and t_{cs} and again between t_{ce} and t_e, it is assumed that persons arrive and depart with constant rates, i.e. $p(t) = (t - t_s)/(t_{cs} - t_s)$ for $t_s \leq t \leq t_{cs}$ and $p(t) = (t - t_{ce})/(t_e - t_{ce})$ for $t_{ce} \leq t \leq t_e$ This implies that the average work duration is $(t_{ce} + t_e)/2 - (t_s + t_{cs})/2$, where, for example, "early" people will work from t_s until t_{ce}, and "late" people from t_{cs} until t_e.

Now a total number of persons n_p and a number of persons n_w going to work on the analyzed day is defined. The number of persons being at work $n_{pw}(t)$ and at home $n_{ph}(t)$ for a certain time t is given by the following equations:

$$n_{pw}(t) = p(t) \cdot n_w \tag{1}$$

$$n_{ph}(t) = n_p - n_{pw}(t) - n_{trav}(t) , \tag{2}$$

where $n_{trav}(t)$ is the number of persons on travel at time t.

It is assumed that the energy consumption for a "typical" office is defined by a saturation function. Thus, the energy consumption rate for all offices $e_o(t)$ is defined with a base load P_{bo} and an additive saturation load P_{so}, resulting in

$$e_o(t) = n_p \cdot (P_{bo} + P_{so} \cdot (1 - e^{-\rho_o(t) \cdot \beta})) , \tag{3}$$

where n_p means that the number of workplaces is the same as the number of persons in the model, $\rho_o(t) = n_{pw}(t)/n_p$ and $\beta > 0$ is a parameter, set to $\beta = 5$ throughout this paper.

Similarly, the energy consumption rate for all homes $e_h(t)$ is approximated with a base load P_{bh} and an additive load P_{ah}:

$$e_h(t) = n_p \cdot P_{bh} + n_{ph}(t) \cdot P_{ah} , \tag{4}$$

where the model assumes that there is either one person at home or none.

For the energy of the daily commute, we define an average daily commute distance d_c and shares of car users s_{car} and pt users s_{pt}. From this we get the share for other modes $s_o = 1 - (s_{car} + s_{pt})$. Further we know about the specific energy consumptions per mode per distance, e_{car}, e_{pt} and e_{other}. Thus, the required energy for the daily commute E_c and the total required energy E_{abs} are defined as:

$$E_c = (E_{car} \cdot s_{car} + E_{pt} \cdot s_{pt} + E_{other} \cdot s_o) \cdot n_w \cdot d_c \text{ and} \tag{5}$$

$$E_{abs}(t) = E_c + \int_{0:00}^{24:00} (e_o(t) + e_h(t)) \, dt . \tag{6}$$

Note that since $p(t)$ is piecewise linear, $\rho_o(t)$ is also piecewise linear, and therefore the integral can be solved analytically.

3.2. Case studies

The following variations are considered:

- The number of persons travelling to work is $23,095$ in one configuration (see Sec. 2.2), and $20,771$ in the other. This models **teleworking**, i.e. some part of the population works at home. The models will assume that each worker selects his or her telecommuting days randomly, that is, it will be assumed that offices are occupied at the reduced level.
- The office core hours, $[t_{cs}...t_{ce}]$, are $[10...14]$ in one configuration, and $[9...15]$ in the other. This models **reduced flexibility**. The idea is that extending the core hours forces people on more similar working hours, thus reducing the time period during which the building needs to be heated.

This leads to 4 case studies, see Tab. 1.

Table 1: Parameter settings for the analytical case studies. 2 & 4 – telecommuting; 3 & 4 – reduced flexibility.

parameter			c1	c2	c3	c4
core hour start	t_{cs}	[h]	10	10	**9**	**9**
core hour end	t_{ce}	[h]	14	14	**15**	**15**
persons total	n_p	[#]	23,095	23,095	23,095	23,095
persons working	n_{pw}	[#]	23,095	**20,771**	23,095	**20,771**

3.3. Additional information

For the analysis of the scenario we investigate the period from midnight to midnight. We set the average work duration, including part-time jobs, to $t_w = 6h$; note that for this, the workplace opening/closing times need to be $[t_s...t_e] = [8...16]$ in the first case, and $[9...15]$ in the second case. That is, the longer core hours go along with a shorter overall office opening and thus heating time.

To analyze the energy consumption we need to know about the installed power for home and work locations for empty and occupied locations per person. We derive plausible numbers as follows. The total annual energy consumption by **households** in Germany is approximately $2\,400\ PJ$.[*] Further the German "Bundesamt für Statistik"[†] states that the total number of dwellings is $36\,089\,000$, and the average number of persons per dwelling is 2.0. Thus, an average person consumes

$$\frac{2\,400\ PJ/yr \cdot 112\ TWh/400\ PJ}{36\,089\,000\ dwellings \cdot 2.0\ persons/dwelling \cdot 365\ days/yr} \approx 25.5\ kWh/(day \cdot person)\,.$$

From the daily energy consumption one may approximate the base load P_{bh} and the additive actual load P_{ah}. Agarwal et al.[4] show the dependency of occupants presence to energy consumption. Although they showed it only for office buildings we assume the same distribution for dwellings, i.e. the off-peak power usage is $\alpha = 30\%$ of the peak usage. Re-writing Eq. (4) for a 24 hr period, we obtain

$$25.5\ kWh \overset{!}{=} 24\,h \cdot P_{bh} + t \cdot P_{ah}\,,$$

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where t is the duration of the person being at home. Together with $P_{bh} = \alpha \cdot (P_{bh} + P_{ah})$ and $t = 17h$ (consistent with 6 hours of work and two times 0.5 hours of commuting), we derive P_{bh} and P_{ah} as shown in Tab. 2.

Table 2: Power settings, specific energy consumption and modeshare.

P_{bo} [kW/Person]	P_{so} [kW/Person]	P_{bh} [kW/Person]	P_{ah} [kW/Person]	E_c [MJ/km]
0.149	0.347	0.400	0.934	1.771
E_{pt}[MJ/km]	E_{other} [J/km]	s_c [%]	s_{pt} [%]	d_c [km]
0.885	0	54.0	25.0	41.5

To derive numbers for **offices** we use the so called German "Technische Regeln für Arbeitsstätten" (ASR A1.2) which define the minimum office size. For the first person a minimum space of 8 m^2 is required. For every further person at least 6 m^2 are required. For reasons of simplicity we assume every work place occupies 8 m^2. The energy consumption E per m^2 and year is $120\,kWh$ for electricity and $100\,kWh$ for heating.[‡] To derive the maximum power per workplace we define a number of working days n_{work} and again an α to describe the off peak usage and a t to describe the working duration. With

$$P_{bo} + P_{so} = \frac{E \cdot 8\,m^2}{n_{work} \cdot (t + (24h - t) \cdot \alpha) + (365 - n_{work}) \cdot 24h \cdot \alpha} \tag{7}$$

and using $n_{work} = 219$, $t = 8h$ and $\alpha = 0.3$, we calculate the maximum power $P_{bo} + P_{so}$ as 0.496 kWh per person. From there, $P_{bo} = 0.3 \cdot 0.496$ and $P_{so} = 0.7 \cdot 0.496$.

The energy parameters for the **transport system** are calculated as follows. For car, we use the average consumption of a usual German middle class car[§] of 5.49 l/100km. One liter gas contains an energy of approx. 43 MJ/kg with a density of 0,75 kg/l. Thus the specific energy E_c is 1.771 MJ/km. As shown in Tab. 2, the commuting distance (morning and evening trip together) is assumed as $41.5\,km$, the modal split as 54% car, 25% public transit, and the remaining 21% non-motorized, and the specific energy consumption when using public transit is assumed as half that of car[¶].

3.4. Results

The results of the energy calculation, displayed in Fig. 2a, display the following characteristics:

- Telecommuting reduces the transport energy, but increases the energy consumed at home by about the same.
- In contrast, the office energy is barely affected.
- Reducing the office heating period by extending the core hours has rather little effect overall.

The reason why telecommuting has so little effect on the office energy is that, because of the non-linear saturation function, there is not much difference once offices are occupied at all. In consequence, reducing the heating time by concentrating the occupancy on fewer hours has rather more effect than telecommuting – still, the effect is not very large. Note that the entire effect of concentrating the office hours is due to the non-linearity of the office energy consumption function – were that function linear, there would not be any effect. Thus, the non-linearity is not strong enough to yield strong results.

Overall, the initial speculation that companies might be able to reduce their energy bill at the expense of their employees is not truly borne out: The savings that the companies could make seem rather small. If companies consider the telecommunication policy in order to save energy, they need to make sure that complete offices are made empty and thus not heated.

[‡] www.energie.ch/buero, accessed 27-nov-2013.
[§] Volkswagen Golf VI, 1,400 ccm, 90kW, see: http://www.adac.de/infotestrat/tests/eco-test/detail.aspx?IDMess=3274, last access: November 27, 2013
[¶] No valid source available, thus we used 50% of the specific energy of car.

4. Simulation

4.1. Approach

To analyze the building energy consumption based on a traffic model the standard MATSim output is used and post processed to derive the necessary data from the generated events. For this the analysis is divided into two parts, a) the analysis of the building energy consumption and b) the analysis of the commute energy Consumption.

For the **Building Energy Analysis** so called *ActivitStart-* and *ActivityEndEvents* are used. These events are generated every time an agent starts or ends an activity on a Link. Using those events the maximum number of activities performed in a certain time slice (taken as 15 min) is counted. The office size per link is defined by the maximum of activities of type "work" on this link, i.e. $n_p = n_{p.link}$. For the calculation of the consumed energy on a certain link with working activities we use Eq. 3 with $n_{pw}(t)$ equals the maximum number of persons working on a link in any time slice. For the energy consumed by home activities we use a variation of Eq. 4 with n_p equals the total number of persons, and $n_{ph}(t)$ equals the number of persons performing a home activity in a certain time slice.

To calculate the **energy consumption of all commuters**, Eq. 5 is used. The distance travelled is calculated for every single trip, i.e. so called *LinkEnter-* and *LinkLeaveEvents* are used to calculate the travel distance. The distance, and thus the consumed energy, is calculated for the whole day plan of all commuters.

4.2. Setup

Based on the scenario described in Sec. 2.2, four different simulation case studies (s1 ... s4) are set up (cf. Tab. 3)

- **s1** is the basecase run, with all parameters unchanged.
- **s2** models **telecommuting** by reducing the number of persons commuting in the travel model by 10%. We assume they will stay the whole day at home.
- **s3** models **reduced temporal flexibility**. The specific values (Tab.3) are different from the analytical model since in the real-world situation, actual work durations vary greatly between persons. In particular, long core hours would not work for many part time jobs.
- **s4** models **telecommuting and longer core hours together**.

Table 3: Setup for simulated case studies

parameter		s1	s2	s3	s4
ActivityOpeningTime_work	[hh:mm]	07:00	07:00	**08:00**	**08:00**
ActivityClosingTime_work	[hh:mm]	19:00	19:00	**17:00**	**17:00**
ActivityTypicalDuration_work	[hh:mm]	06:30	06:30	06:30	06:30
ActivityLatestStartTime_work	[hh:mm]	13:00	13:00	**12:00**	**12:00**
persons total	[#]	56,160	56,160	56,160	56,160
persons working	[#]	23,095	23,095	23,095	23,095
persons commuting	[#]	23,095	**20,771**	23,095	**20,771**

For all studies 300 iterations were run. Innovative replanning modules (routing, departure time modification) were disabled after 240 iterations. For the building energy analysis the period is split into 144 time slices k with a duration $t_d = 0.25h$. The energy consumptions parameters from Tab. 2 are used here as well.

4.3. Results

The simulation results (Fig. 2b) confirm the results of the analytical model of Sec. 3, albeit with different values. In particular, the additional energy consumption when staying at home is now *more* than the saved travel energy. This is due to the fact that the model assumes that *all* non-home activities are moved to home when synthetic persons take their telecommuting day. Fig. 3 shows how the change of the office opening times/core hours affects the probability

Table 4: Results for simulated case studies. 2 & 4 – telecommuting; 3 & 4 – reduced flexibility.

		s1	s2	s3	s4
avg. trip distance (car-commuter)	[km]	14.66	14.56	14.63	14.56
avg. trip traveltime (car-commuter)	[min]	39.64	35.38	41.19	36.26

of being at work: The model predicts fewer workers at early and late yours. The model, in fact, predicts fewer work hours overall – presumably, this is the reaction of MATSim's scheduling algorithm to the stronger constraints.
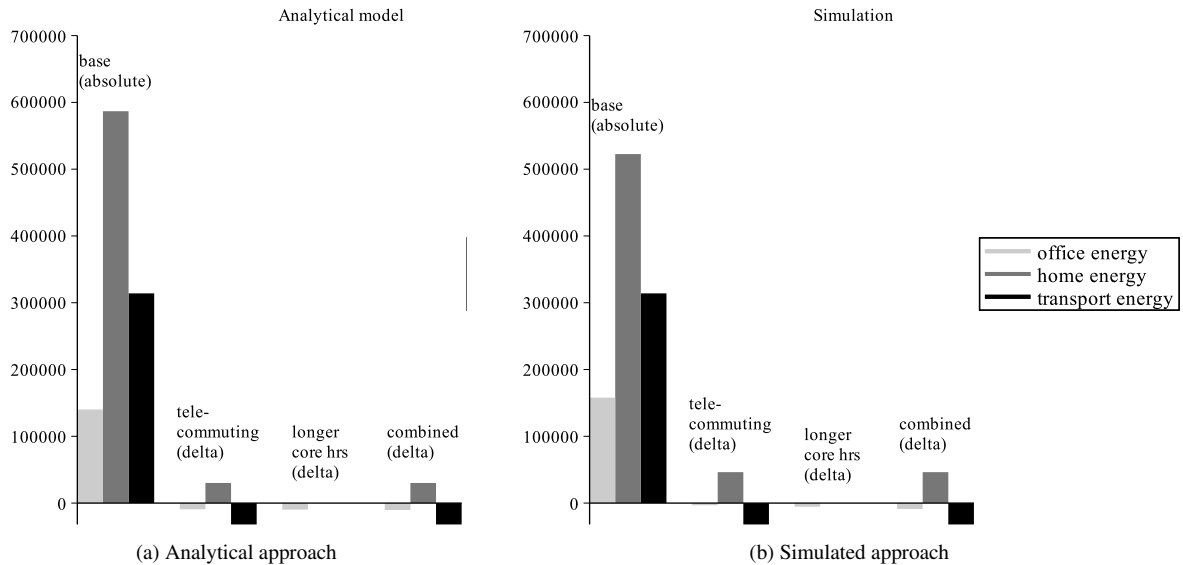

Fig. 2: Energy consumptions for the one percent sample. The first data triple are absolute consumptions (base case); the next three data triples are differences compared to the base case.

The most significant difference is actually in the congestion times, see Tab. 4: reducing flexibility clearly increases congestion (s3 vs. s1 and s4 vs. s2). In contrast, introducing telecommuting clearly reduces congestion (s2 vs. s1 and s4 vs. s3). Still, the congestion effect of the reduced flexibility is probably less than anticipated. Reasons may be that, in Berlin, commuting is only about 20% of the demand [15], and that, because of the many part-time jobs, even the reduced workplace opening time leave quite some flexibility.

5. Discussion

While the transport model is fairly sophisticated, other parts of the model are arguably somewhat ad-hoc. There are, however, structural statements which we expect to hold up with any model:

- The energy consumption of the transport system is essentially proportional to the distance. As a result, the 10% reduction of commuter mileage because of telecommuting has a much stronger effect than the congestion differences by the changes in the office opening hours.
- The savings in transport energy are offset by more consumption of energy at home, although the increase of home energy consumption are probably overstated, since not everybody is living alone or in a dual worker household as the model assumes.
- It seems plausible that individuals consume less space in offices than at home. Also, it is probably easier to make office buildings energy efficient rather than homes. Thus, once people are at their offices, they are probably more energy efficient there than at their homes.
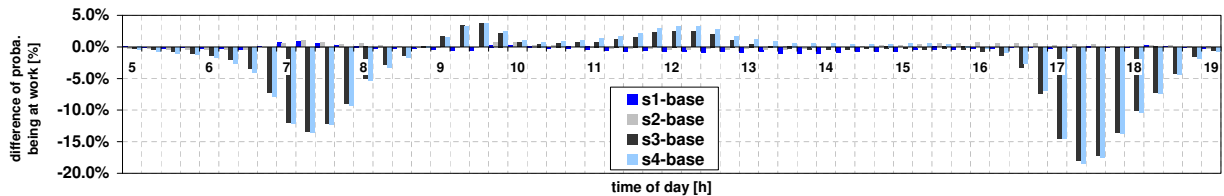
Fig. 3: Differences to the base case (s1) of the probability of being at work. 2 & 4 – telecommuting; 3 & 4 – reduced flexibility.

6. Conclusion

The presented work shows that it is possible to derive information about activity scheduling from a microscopic traffic model. This information may be delivered to a building energy consumption model. For this work a simple model without any detailed information about building specific consumption profiles is used.

The results show a) the consequences of telecommuting to a traffic system and b) the consequences to the resulting energy consumption. As a tendency, telecommuting increases home consumption, reduces transport energy, and does not change office energy consumption very much. The last result hinges on the assumption that telecommuting days are selected randomly, meaning that all offices are somewhat affected, rather than emptying out fewer offices completely. In contrast, changing the office opening times/core hours has rather little effect in terms of energy consumption. The most noteable effect is an increase in congestion.

Overall, it seems that neither of these two measures – telecommuting or reducing flexibility – offers an easy handle to reduce energy consumption. Maybe as importantly, there is little incentive for employers/offices to use one of the two measures to "push" the energy consumption into different sectors of the economy, since their own savings would not be very large.

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