Modeling the Labor Market in the Aftermath of a Disaster: Two Perspectives

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Abstract: This paper presents two opposite perspectives on the labor market in the aftermath of a disaster. The first posits a production sector that is non-tradeable and a labor market with total mobility. This is modeled using agent based simulation. The second presents a production sector that is fully tradeable and a labor market that is perfectly immobile. This is modeled using traditional micro-economic modeling and numerical simulation. Outcomes from the two approaches are compared. In the no-disaster case, participation rates and wages under both approaches settle down to a low-level equilibrium albeit at different rates. In the case of a disaster, outcomes are very different. Under the agent based model, labor market mobility results in solutions being found outside the area. In the micro-economic approach workers absorb the recovery process within the area readjusting their demand for labor. When population movement is introduced the system reorganizes at a new equilibrium. The results highlight first, the importance of labor mobility and flexibility and second, the divergent absorption costs in determining the long-term outcomes of a disaster.

Key words: labor markets, agent based simulation, numerical simulation, equilibrium, adjustment

1. Introduction

Cities are often spatially organized around the concept of work and commuting. As such, the labor market forms one of the central features of the urban environment and the sole source of income from wages. Spatial rigidities in the location of firms and employees allow for idiosyncratic regional labor markets which affect population levels, incomes, firm competitiveness, and commuting. By altering these core characteristics of the city, the labor market spatially and functionally organizes urban space (Lowry 1964, Scott 1988). A significant shock to local capital via a large-scale disaster will catalyse a decline in worker productivity (Bascarino et al., 2006). While the result of this decline is subject to debate (Loayza et al., 2009) there is little doubt that the subsequent recovery of productivity is inherently linked to reconstruction and thus to both land use and population size. Hence, in order to articulate the consequences of a large-scale urban disaster, due consideration must be given to the disruption caused to the labor market and its recovery process. In particular, discussion of urban resilience must acknowledge the sensitivity of the urban labor market to capital shocks.

Market dynamics determine prices and quantities for two sets of agents – producers and consumers. In the context of the labor market these producers are residents and the determination of prices and quantity serves as a determination of income. Correspondingly, this collection of prices and quantities determines, ceteris paribus, output and profitability. In a general equilibrium setting for a closed economy, these dual effects are constituted when market equilibrium is determined.

Local labor markets bifurcate these effects into an effect on resident income and an effect on local firm output and profitability. In such a setting, not all labor income is derived or distributed locally due to the existence of 'out of region' workers and employers. Additionally, if firms are able to export their product, they engage demand that is not solely generated by resident income and is partially independent of local demand. In reality, the urban labor market is a mixture of geographic and economic interactions and can often itself be aggregated into other 'local' sub-markets. No pure 'closed' market exists, and local sub-markets exhibit varying degrees of 'openness' to outside markets.

Disasters such as earthquakes have a destructive effect on buildings, infrastructure and machines. We model this effect as a precipitous reduction in capital stock. Assuming production is comprised of this capital and labor, the law of diminishing returns suggests a sharp reduction in capital would cause a parallel decline in worker productivity. Classical market equilibrium conditions require that this befollowed by an immediate fall in wages. However empirical evidence following both Hurricane Katrina (Deryugina et al. 2014; Groen et al. 2015) and the 2010 and 2011 earthquakes in New Zealand (Fabling et al. 2016) suggests otherwise. These disasters were followed by immediate reductions in employment, rather than wages. This may be a manifestation of "wage rigidities". These have been recognized as an important force in driving unemployment and explaining the lack of responsiveness of wages to business cycles (Hall 2005a; Haefkea et al. 2013; Fehr and. Goette 2005; Costain and Reiter 2008; Kennan 2010; Shimmer 2005).

To study the sensitivity of the urban recovery process and post-disaster equilibrium we present two alternative perspectives on the labor market. In the first, we assume that the labor market is completely open. That is, all workers are free to leave the area and pursue readily available employment outside the region of interest. In this case, we also assume all employers may hire employees living (and consuming) outside this region. However, all products are non-tradeable and all revenue is derived locally. The second perspective is the opposite. Rather than labor being spatially mobile, the product market is now completely tradeable. All goods may be sold outside the region but labor is perfectly immobile, i.e. no labor is traded between the region of interest and the rest of the world. Essentially, these two extremes are categorized by a totally inelastic demand curve with no spatial friction for either labor or the aggregate good.

The paper proceeds by presenting two simulations of post-disaster urban dynamics which highlight the importance of the labor market and its relative 'openness'. We use a different method in each case. To demonstrate the first case, we use an agent based (AB) simulation. This is the natural framework when the assumption is that labor is perfectly mobile and tradeable and allows for a simple, yet rich, incorporation of spatial elements. Since non-tradable goods exhibit the strongest spatial friction (for example restaurants or construction are inherently not mobile), we believe this to be a vital element. For the second case, we present a numerical simulation of aggregate labor dynamics. The motivation for each method is elaborated below. We conclude with a discussion comparing the results produced by the two simulations and the implications they offer for modeling and understanding labor markets in the wake of an urban disaster.

2. Agent-Based Simulation of the Labor Market

Given the interdependencies between a non-tradeable production sector and space, a comprehensive approach to modelling the urban system is required. Changes to the labor market in the aftermath of a disaster adjust the flows of people and income within this spatially rigid system. However, the land use which sustains the non-tradeable production sector is a stock. This makes such integration difficult to implement due to the complex geographical nature of the urban system. An elegant solution is offered by agent-based models which conceptualize the dynamics of a system as emerging from the behavior of its most fundamental, atomic, components and from their interactions with the environment and with each other. This bottom-up approach can help in simplifying the analysis of complex systems behavior. It requires only three basic definitions: (1) defining the atomic entities (i.e. 'agents') and their attributes, (2) defining the environment and its attributes, and (3) defining the rules guiding the behavior of agents. While AB models have been applied in disaster studies (Chaturvedi et al,2005) they have not been spatially explicit and have generally been set in hypothetical rather than real-world environments. The current model builds on previous work (Grinberger & Felsenstein, 2016) and identifies building-block agents as city residents (individuals and households). They function as the unifying element that bridges housing, land-use and labor sub-systems. With respect to housing and land use markets, agent behavior animates demand side dynamics. For the labor market they represent the source of labor demand.

Normally a full articulation of these sub-systems would include the dynamics of both supply and demand. However, this would require introducing many more agent sets into the model (such as entrepreneurs, contractors, firms and municipal authorities) thereby increasing model complexity. To by-pass this constraint, we break with tradition of conceptualizing the environment as a passive element within AB models and define 'quasi-agent' status for physical entities such as buildings, local housing markets, and jobs (see Appendix 1 for a detailed account of the different entities included in the model). These entities are not mobile or able to initiate actions like regular agents but are comprised of traits that change according to pre-defined environmental sensitivity rules. In this sense, they resemble cells from a cellular automata model.

The current model simulates disaster outcomes relating to both stock and flow attributes of the urban environment (Figure 1). Stock attributes refer to changes in land use residential and non-residential capital. Flow attributes relate to labor market conditions post disaster. The two are dynamically and spatially related. A large-scale shock to the urban system has a powerful, brief effect that links stocks to flows. It rapidly reduces capital stocks and generates social changes altering the local demographic composition. This has particular labor market effects that exert a downward force on wages initially driven by a change in marginal productivity generated by the sudden decline in capital stock. While damage to physical stock is dramatic, visible and easily simulated, flow effects are harder to capture. Physical destruction can also have an indirect effect on the labor market represented by labor market outcomes such as wage-levels, workforce participation, and job occupancy (Figure 1). We now discuss how we simulate dynamics within the labor market and the other sub-systems in the model.

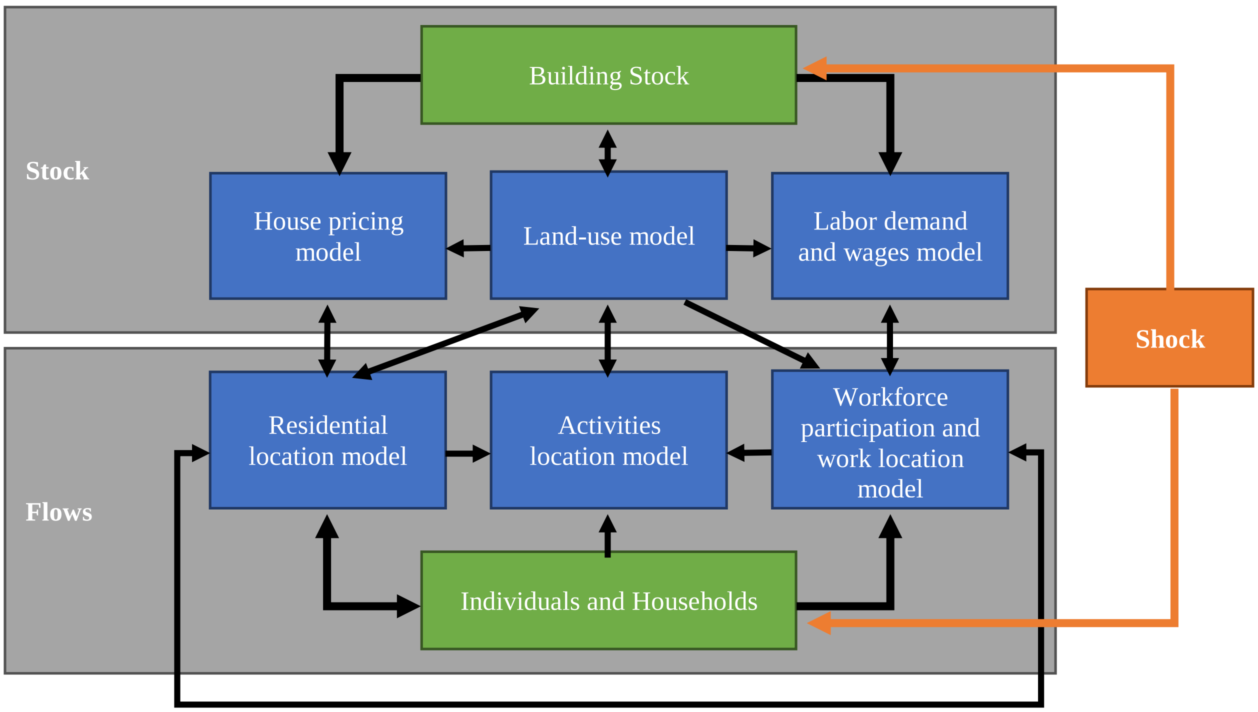


Figure 1. An Agent-Based Framework for Simulating the Effects of Urban Disasters

2.1 The Labor Market

Agent-based models operate bottom-up to simulate environmental changes that affect subsequent rounds of decision-making. Along with the definition of individuals and households as basic agents this has implications for modeling the labor market. First, labor market concepts such as equilibrium wage, matching friction and wage rigidities, cannot be considered as system-wide top-down parameters. Rather they are treated as variables resulting from the dynamics between agents and their environment. For example, matching friction emerges from agent attributes such as level of knowledge and flexibility of preferences, rather than from pre-defined system-level parameters.

Second and more importantly, the AB approach tends naturally towards conceptualizing the labor market as characterized by tradeable and perfectly mobile labor and a spatially rigid product market. Accordingly, we do not directly simulate the behavior of firms but include a set of quasi-agent job entities characterized by wage, location, and job vacancy status (unoccupied, occupied by agents, occupied by non-residents). The number of available jobs is defined by floor-space volume and land-use specific job-density parameters (see section 2.3 and Appendix 2). In order to illustrate how demand for employees per building reacts to change within the market we introduce a top-down process governing the wage local employers would have paid in a closed, local equilibrium. We term this the local clearing wage. Note however, that in reality firms must compete with perfectly elastic 'external' demand for employees. We base the local clearing wage on an intra-temporal linear approximation of the marginal product of labor derived from a Cobb-Douglas production function (Eq. 1; see section 3 for details).

$$(1)\ \log\left(\frac{W_t}{W_{t-1}}\right) = \alpha \cdot \log\left(\frac{K_t}{K_{t-1}}\right) + (\beta - 1) \cdot \log\left(\frac{L_t}{L_{t-1}}\right) \rightarrow W_t = W_{t-1} \cdot \frac{K_t^{\alpha}}{K_{t-1}^{\alpha} \cdot \left(\frac{L_{d,t}}{L_{d,t-1}}\right)^{1-\beta}}$$

where W_t, K_t, $L_{d,t}$ represent average wage levels, capital stock levels, and the demand for labor at time *t* respectively. β, α are Cobb Douglas parameters (see section 3 for further details).

Floor-space volume represents capital stock while the share of occupied jobs out of total jobs represents demand for labor. The change in global average wage affects wage levels at all available positions skewing the distribution of wages by the difference between W_t and W_{t-1}, i.e. this value accrues to each individual job's wage level. It is important to note that this procedure affects unoccupied jobs only. The wages of occupied jobs remain constant as long as the position is filled, reflecting a form of wage rigidity.

The supply side of the labor market is represented by the behavior of individual agents. At each iteration agents perform several actions such as joining the workforce, searching for a new job, choosing to commute from the study area or dropping out of the workforce (for unemployed agents included in the workforce). The first action is informed by changes to the average wage parameter, i.e. the chance for an agent to join the workforce is dependent upon the ratio between the new average wage and the previous wage.

Agents participating in the labor force but currently unemployed continuously search for a job. The choice of a specific workplace is random based on an attractiveness score related to commuting distance and a min-max normalized value of the offered wage. This score is compared to agent preferences derived either from previous work location or drawn randomly. This process is equivalent to assuming that wages are evaluated in a relative manner and that individuals substitute commuting distance with wage levels, meaning they would be willing to accept a lower-paying job if it would reduce commuting [1]:

$$(2)\ S_j = \omega_{d,j} * \frac{d_{b_{h:id_h=h_i} \to b_j}}{max\{d_{b \to k}: k \in buildings\}} + (1-\omega_{d,j}) * \frac{w_j - min\{w_k: k \in jobs_{unoccupied}\}}{max\{w_k: k \in jobs_{unoccupied}\} - min\{w_k: k \in jobs_{unoccupied}\}}$$

Every job-seeking agent views up to 7 different available positions. If an agent fails to find a suitable job, there is a chance it will decide to commute outside the study area or leave the workforce. These two options become more probable as the job-seeking processes continues. Given the small size of the study area (see below), we assume unlimited demand for labor outside the study area and negligible spatial friction. Whenever an agent chooses to commute it will find a suitable job (paying a wage equal to its expected income, i.e. the I_{exp} variable; see Appendix 2). If the agent finds a suitable job within the study area, income, expected income, and preferences are updated accordingly.

2.2 The Housing Market

The dynamics of the housing market are determined by the behavior of three types of entities: households, local housing markets (LHM's) and buildings. The probabilistic decisions of households to relocate represent the bottom-up section of this system where such movements affect the supply of housing and possibly also job occupation (in the case where a household moves out and its employed members do not keep their job). The residential location search process in the case of relocation is based on identifying the set of buildings available for the household (i.e. buildings which are (a) undamaged, (b) of empty/residential land-use, (c) not fully occupied, (d) present rent levels below a third of household income). This set is then searched in a random order for a building attractive enough for the agent, where attractiveness is related to commuting distances and the socio-demographic nature of the neighborhood (see Eq. 3) and a utility level set

[1] The formulation of all equations in this section relies on the definitions detailed in Appendix 1 and on the parameters included in Table A1.

by the agent's current housing location (or set randomly for in-migrating households). This process reflects two behavioral assumptions: that households prefer to live among similar households and that individuals aspire to minimize commuting. If the chosen building is empty its land-use changes to residential and new jobs and apartments are created accordingly[2]. If the search fails, i.e. no building with a score below the agent's utility level (and after 100 matching attempts) is inspected or the set is exhausted, then the household moves out.

$$(3)\ S_b = 0.25\Phi\left(\frac{\overline{age}_{i:h_i=h} - \overline{age}_{i:h_i\in h:b_h\in B}}{\sigma_{age_{i:h_i\in h:b_h\in B}}}\right) + 0.25\Phi\left(\frac{i_h - \bar{\imath}_{h:b_h\in B}}{\sigma_{i_{h:b_h\in B}}}\right) + 0.5\left(\frac{\bar{d}_{b\to b_j:j\in job_i:h_i\in h}}{max\{d_{b\to k}:k\epsilon buildings\}}\right)$$

where:
σ_x is the standard deviation of *x*,
$\Phi(x)$ is the standard probability density value for *x*,
B is the set of buildings within a 100 meters distance from building *b*,
$d_{x\to y}$ is the road-network-based distance between a and b.

Following these calculations, changes to average housing price levels are computed for each LHM, based on change in the size of population (i.e. demand), the size of the housing stock (i.e. supply), and the size of the non-residential stock (i.e. service-level; Eq. 4.1). This change in prices trickles down to the level of individual building where average housing price is adjusted to its local service-level (Eq. 4.2). Finally, the overall value of a building is converted to monthly apartment rent[3] (Eq. 4.3). In this way, buildings and LHM quasi-agents become sensitive to indirect changes affecting them:

$$(4.1) hp_{c,t} = hp_{c,t-1} * \left(1 + log_{10}\left(\frac{\left(\frac{\#\left\{h:b_h\in\{id_b:b\cap c\}\right\}_t}{\#\left\{h:b_h\in\{id_b:b\cap c\}\right\}_{t-1}} + \frac{\#\left\{\{b\cap c\}\cap\{b:lu_b=residential\}\right\}_{t-1}}{\#\left\{\{b\cap c\}\cap\{b:lu_b=residential\}\right\}_t} + \frac{\#\left\{\{b\cap c\}\cap\left\{b:lu_b\in\{commerical,public\}\right\}\right\}_t}{\#\left\{\{b\cap c\}\cap\left\{b:lu_b\in\{commerical,public\}\right\}\right\}_{t-1}}\right)}{3}\right)\right)$$

[2] See land-use model below.
[3] The number of apartments is set by the initial number of residents in the building or by dividing building floor-space by 90sqm (representative apartment size).

$$(4.2)\ val_{b,t} = hp_{c\ni b,t} * \frac{\#\{\{a\in B\}\cap\{k: lu_k \in \{commercial, public\}\}\} / \#\{\{a\in B\}\cap\{k: lu_k = residential\}\}}{\#\{a\cap(c\ni b)\cap\{k: lu_k \in \{commercial, public\}\}\} / \#\{\{a\cap(c\ni b)\}\cap\{k: lu_k = residential\}\}} * fs_b$$

$$(4.3)\ rent_b = med\{i_h : h \in households\} * \left(1 + \frac{val_b / ap_b - \overline{\{val_a : a\in buildings\}}}{12 * \sigma_{\{val_a : a\in buildings\}}}\right) * N$$

where:
med(x) is the median value of set *x*,
σ_x is the standard deviation value of set *x*,
N is a normalization factor (see Table A1)
B is the set of buildings within 100 radius of *b*.

The model also considers in-migration, allowing for the generation of new households at each iteration. The number of potential in-migrating households varies with housing supply defined as the number of available apartments multiplied by a random number drawn from a normal distribution with the parameters *in_mig,* σ_{in_mig} (see Table A1). The household is stochastically characterized based on the characterization of the initial population of agents. Only households for whom the residential search process discussed above ends successfully, are added to the set of agents. Locally employed household members attempt to find a job and daily routines are computed for all members[4].

2.3 Activity Location and Land-Use

These sub-models determine the everyday behavior of individual agents and the direct and indirect effects this behavior has on the spatial distribution of land-uses. For each individual, the agent-level model articulates a routine consisting of a sequence of visits to different buildings and the road network routes between them. The exact number of activities is set probabilistically, relying on the agent's mobility profile (age, disability, and car ownership) and employment status (unemployed, employed locally, out-commuter; Eq. 5):

[4] See description of job-seeking behavior above

(5) $A\_num_i = \left\| \left(actNum - 0.5 * (Job_i \ is \ not \ null)\right) * p_i * \left(1 + \omega_{mob} * \left(car_{h:id_h=h_i} - d_i - 1 * (age_i \neq adult)\right) + 1 * (job_i \epsilon jobs)\right) \right\|$

where p_i is a randomly drawn preference value, ranging between 0 and 1.

The first activity of locally employed agents is always located at their workplace. The exact locations of all other activities are set probabilistically. An agent chooses a random building out of the set of buildings that (a) are not empty,(b) are accessible from the location of the last activity (starting from home) given the state of the road network and (c) have an attractiveness score lower than a randomly drawn preference value. The road-network distance from the location of the last activity, the 'riskiness' of the building's environment (the rate of land-use occupancy near the building) and non-residential floor-space volume are all used to compute the attractiveness score of potential locations (Eq. 6). This represents several behavioral assumptions: distance minimization, risk avoidance and preference for scale.

(6) $S_b = \frac{\omega_n * \#\{\{a \epsilon B\} \cap \{k : lu_k = empty\}\} / \#\{a \epsilon B\}}{\omega_n + \omega_d + \omega_{fs} * (lu_b \epsilon \{commercial, public\})} + \frac{\omega_d * \left(1 - d_{b-1 \to b} * \left(1 - \omega_{mob} * \left(car_{h:id_h=h_i} - 1 * (age_i \neq adult)\right)\right) / max\{d_{b \to k} : k \epsilon buildings\}\right)}{\omega_n + \omega_d + \omega_{fs} * (lu_b \epsilon \{commercial, public\})} + \frac{(lu_b \epsilon \{commercial, public\}) * \omega_{fs} * fs_b / max\{fs_k : k \epsilon buildings\}}{\omega_n + \omega_d + \omega_{fs} * (lu_b \epsilon \{commercial, public\})}$

where *b-1* indicates the location of previous activity,

d indicates road-network shortest-route distance.

To reduce computational overload, these routines generally remain constant throughout the simulation and are adjusted only in certain cases. For example, when households change residence, when agents change employment status or job, when buildings change their land-use or when a blocked road becomes usable again. Route selection uses Dijkstra's shortest-path algorithm. These routes are then used to compute average traffic values (over last 30 iterations) which inform land-use dynamics. We assume that the more traffic flows near a building, the greater its economic potential and the larger the building in terms of floor-space[5], the larger the magnitude of flows needed to sustain its viability. Consequently, for each iteration a local correlation score is computed per building (Eq. 7.1). Residential and empty buildings recording scores larger than 99.95% become commercial since proximate traffic flows are high relative to their floor-space. Commercial buildings recording score levels in the range between $S_b(1)$-0.01 and $S_b(1)$ become empty. These values are chosen to decrease the sensitivity of larger commercial functions to traffic flows. The computation assumes an exponential distribution of both measures. As such, the score values are akin to comparing rankings within the distributions of the two measures. These changes affect the labor market where existing jobs are lost and new jobs are created in accordance with the job density per use parameter[6].

(7.1) $S_b = \frac{e^{-\Delta}}{1+e^{-\Delta}}$

where:

(7.2) $\Delta = \frac{z_{traff} - z_{fs}}{|z_{fs}|}$

where Z_{traff}, Z_{fs} are accordingly local traffic and floor-space scores, computed as follows:

(7.3.1) $Z_{traff} = \frac{e^{\overline{\{a\_traff_r : r \in R\}} / \overline{\{a\_traff_r : r \in roads\}}} - e^{med\{a\_traff_r : r \in roads\} / \overline{\{a\_traff_r : r \in roads\}}}}{\overline{\{a\_traff_r : r \in roads\}}}$

(7.3.2) $Z_{fs} = \frac{e^{fs_b / \overline{\{fs_a : a \in buildings\}}} - e^{med\{fs_a : a \in buildings\} / \overline{\{fs_a : a \in buildings\}}}}{\overline{\{fs_a : a \in buildings\}}}$

where *R* is the set of roads adjacent to building *B* (i.e. one of their nodes is the node closest to the building).

3. Case Study: An Earthquake in the Jerusalem City Center

3.1 The Study Area and Data

We simulate agent based labor market outcomes of an earthquake in the real-world environment of Jerusalem's city center. This is a mixed land use area 1.45 km^2 in size housing 717 residential buildings (243,000 m^2), 179 public-use buildings (420,000 m^2), and 119 commercial structures

[5] Buildings are classified into four uses – empty, residential, commercial (assumed to include only retail), and public.

[6] Note that buildings may also change their land-use under other circumstances- for example if an empty structure becomes occupied by a household (changes to residential), and that public retain their use, even after they are rebuilt.

(505,000 m^2), including two major commercial locations, the city centre and the Machaneh Yehuda enclosed market, and is traversed by a number of major roads (Figure 2). 8,665 households and 22,243 individuals reside in this area and the labor force includes many in-commuters. The location of the area is only 30 km away from the active Dead Sea fault. It also houses many structures that do not ascribe to modern building codes pointing to the feasibility of an earthquake scenario for the area (Salamon et al., 2010).

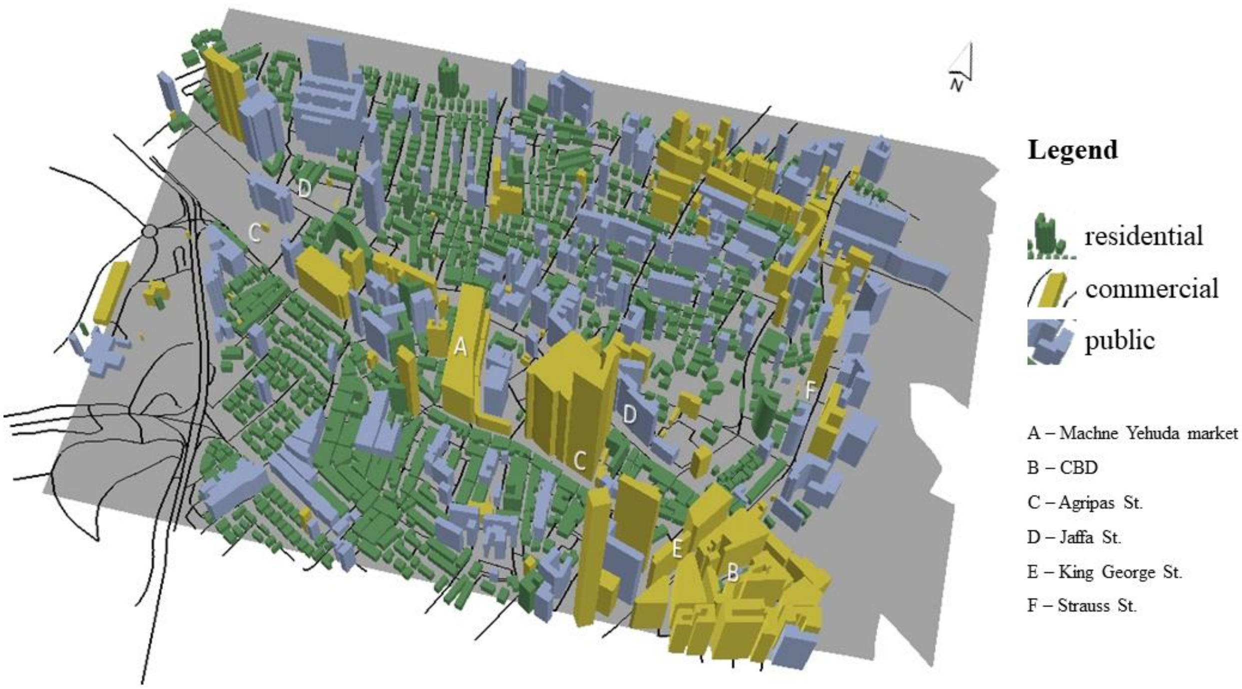


Figure 2. The Study Area: height represents number of floors.

We run the model 25 times with no shock and 25 times with a shock, located randomly in space (to avoid spatially biased results), occurring at day 60. This run-in period, where land-use changes are allowed only after the first 30 days, is chosen so that the system can reorganize according to the simulation dynamics before the shock. The simulations run for three years after the shock.

The initial sets of agents and entities are derived from available datasets: detailed information on buildings and roads comes from the Israel Land Survey, including building heights and land-uses, and socio-demographic data from the Israeli Central Bureau of Statistics. As this last set is only available at the aggregated Statistical Area (SA, i.e. census tract) level, a previously developed disaggregation procedure employing an iterative allocation process (Grinberger and

Felsenstein 2017a) is used to create synthetic representations of all individuals and households in the area. This process first creates individuals and then characterizes them over the multiple required traits while keeping SA-level control totals. It then groups them into households and finally allocates each household to a residential building based on a ranking and matching approach. The resulting population presents a high-resolution representation of the urban environment that is synthetic for specific observations yet corresponds to SA-level distributions. Jobs are also created synthetically, based on the distribution of floor-space by land-use and the job density parameter (Appendix 1). Wage levels are drawn randomly from a normal distribution defined by the average wage and its standard deviation value. All agents participating in the workforce are assumed to be employed at the beginning of the simulation, and each agent is allocated to the job offering a wage closest to the agent's expected income (derived from the disaggregation procedure). All jobs not assigned to residents are assumed to be occupied by commuters.

3.2 Results

We present aggregate results for key labor market parameters, using indicators such as changes in population over time, average wages, job occupancy rates, labor force participation and floor-space volume by use. Changes in wages are represented by both the value of the top-down, local clearing wage (see Section 2.1) and the actual average wage of unoccupied jobs. The former represent the reaction of the demand side of the market while the latter describes what happens when this reaction is integrated into decision-making processes on the supply side. For example, wage offers may increase but actual average wage may remain the same if all higher-paying jobs become occupied.

Figure 3 presents changes in building stock sizes and floor-space volumes by use, averaged over all simulations by scenario. First, it is important to note that at t=30 the size of non-residential stock increases (by about 120 buildings) at the expense of residential stock. This is due to the simulation not activating the land-use change model during the 30-day run-in period. This result, derived from the unrealistic absence of land-use regulation constraints, makes it more useful to treat t=30 as the true beginning of the simulation.

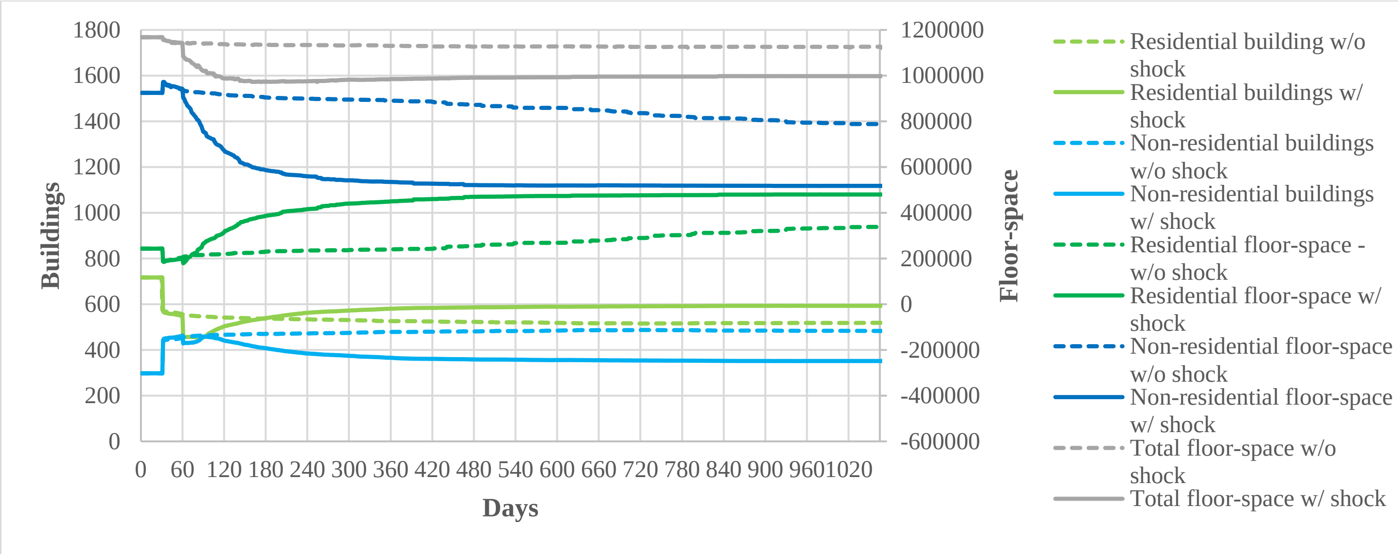


Fig. 3. Dynamics of change in building stock and floor-space volume by land-use and scenario.

The direct effect of a shock is clearly visible with both capital stock and floor-space volumes declining rapidly at t=60. A longer-term indirect effect is also evident in the decrease in commercial stock both in terms of size and of volume. This decline parallels increasing residential uses both in number and size. Because of damage-related constraints to mobility, some surviving commercial venues become untenable. In addition, by the time reconstruction starts, new mobility patterns emerge that make previously successful venues currently less feasible.

These patterns also have a dual effect on the labor market. Less commercial space means less jobs (due to jobs density values). Equation 1 implies that a general decrease in total floor-space reduces the local clearing wage parameter. Figure 4 represents effects on the demand for labor, i.e. changes to the status of jobs within the study area and the wages offered by firms. One prominent result is that the regional clearing wage parameter suffers from the direct effects of the shock and plunges, since the loss of capital stock is much greater than the decrease in occupation rates (which are also directly affected). Offered wages (wages for unoccupied jobs) seem however to increase. This is not a real trend but only a technical convergence of values towards the average[7].

[7] The shock leads to the creation of new jobs whose wages are randomly drawn based on the parameter value; pre-shock average offered wages are much lower than the parameter values. Hence these new jobs push up the value of this variable making this a correction rather than a meaningful result. The values never reach the parameter value since higher-paying jobs are more easily occupied, meaning the value of this variable is always below the parameter value.

Clearing wages do seem to recover over time to values close to pre-shock conditions and stabilize along with offered wages (for whom the equilibrium value is lower than that achieved under the no-shock scenario). This process however happens at a relatively slow rate, suggesting that wages continue to be more affected by the availability of capital stock than by occupancy rates. Indeed, wages stabilize when changes to floor-space volumes become negligible. This is due to the interdependence of wages, agent behavior and occupancy. The initial drop in occupancy rates is related to the matching friction caused by agents' limited ability to identify relevant opportunities. As this drop is accompanied by a decrease in wages, the demand for labor fails over the long-term to offer opportunities that are attractive relative to worker demands. Hence participation rates stabilize quite quickly and leave wages to be determined solely by the slow pace of the stock-oriented reconstruction process.

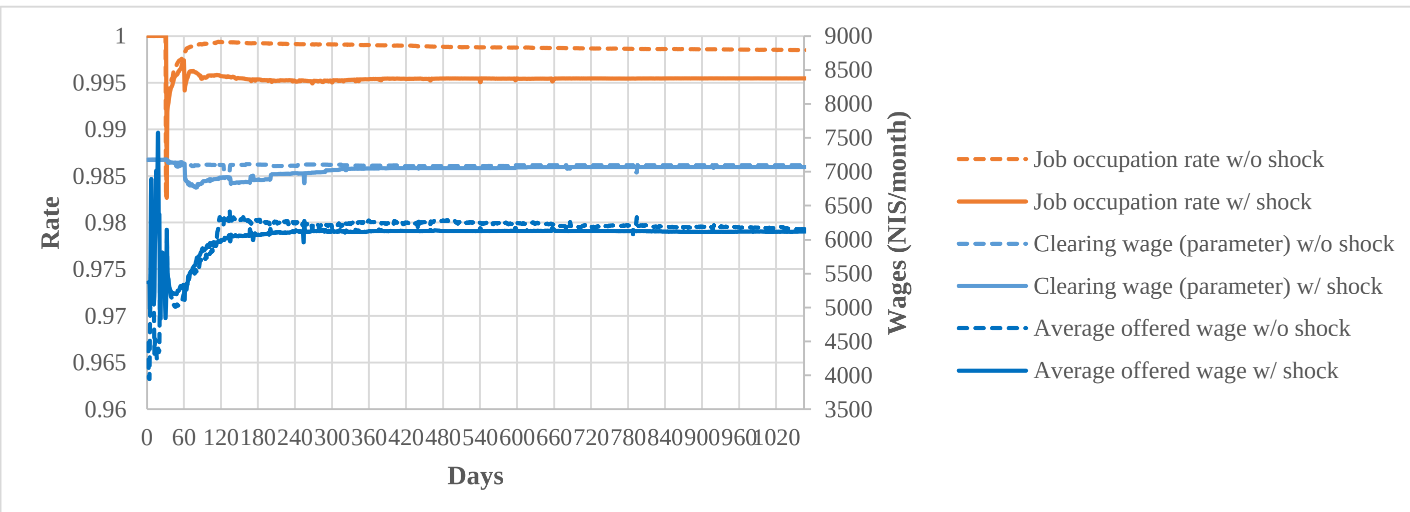


Fig 4. Dynamics of change in wages and job occupancy rate by scenario.

As workers are mobile, they are more flexible and respond much more quickly to these changes. The situation after the earthquake, where a surplus of workers emerges due to falling demand and the decline in attractiveness of available opportunities, is thus unsustainable. Unemployed agents are forced to find other work solutions either by commuting or by opting out of the workforce. This pushes down both participation and local employment rates at a much faster rate than in the no-shock scenario, until stabilizing on a low-level stable equilibrium (Fig. 5). This result is accentuated by population growth experienced due to increased supply of housing (Fig.

5). Since some migrants start-off as commuters, local employment rates suffer more than workforce participation and experience a much sharper decline.

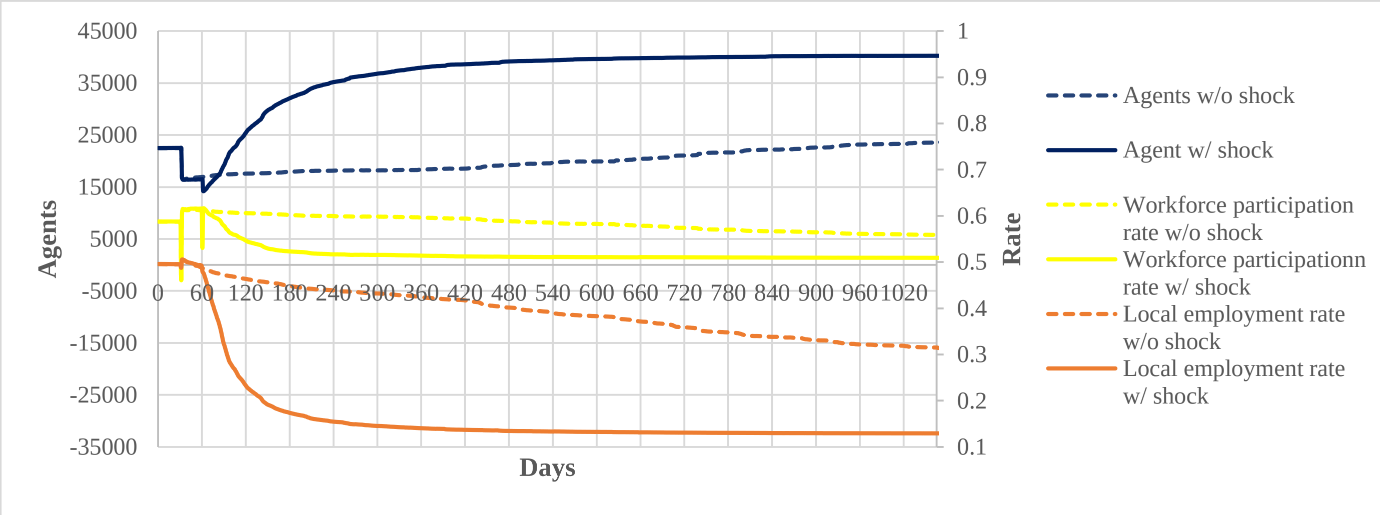


Fig 5. Dynamics of change in population, labor force participation and local employment by scenario.

These dynamics do not just portray land use shifts towards residential uses but also a local workforce that becomes more dominated by commuters. The city center area experiences a suburbanization trend which reduces total production in the region. This is not due to declining worker productivity but to a change in the mixture of products offered within area. The replacement of productive firms by residents who choose to produce in other regions only amplifies this trend reducing local productivity.

4. Numerical Simulation of the Post-Disaster Labor Market

In this section we examine the post-disaster recovery process from an opposite perspective to that simulated in the agent based model. Using numerical simulation we present an urban area in which the production sector is entirely tradeable i.e. produced goods are exportable at no spatial cost to a large outer market. In this outer market firms cannot affect price and demand is totally elastic. Therefore, a disaster does not affect demand for a firm's output – only the price of its inputs. These inputs include labor and capital, both of which are non-tradeable and whose price thus fluctuates post disaster. In contrast to the market for products, we initially assume labor to be immobile and non-tradeable, i.e. employers and employees cannot hire or be hired in other regional markets. Our methodology of choice is a more orthodox economic approach. We model the behavior of firms and workers using a representative version of each and examine the aggregate market results. Firms are homogenous, whereas workers are heterogeneous, but conform to the same distribution.

To this end, we make a set of assumptions about the economic behavior of individuals and firms. To articulate the demand side of the labor market, we assume that firms act as profit maximizers and that the aggregate production function is of a Cobb-Douglas type, composed of labor, capital, and regional infrastructure. We further assume two types of labor market imperfections: a) wage rigidities such as those described above, and b) employment matching imperfections such that a certain percentage of job seekers fail to find available positions.

4.1 Labor Demand and Immediate Post-Earthquake Unemployment:

Our goal in developing this model is not to fully explain the complexity of the labor market. We are not concerned in the full effects of labor on the general equilibrium of the city, such as the relation of wages and local demand, or interest. Rather, we limit ourselves to studying the post disaster dynamics, particularly of wages and employment demand and supply.

Based on the regional production function (Eq. 8), the firms' profit function, at time t, can be described (Eq. 9).

(8) $F(K,L) = A \cdot K^{\alpha} \cdot L^{\beta} \cdot I^{\gamma}$

$$X - General\ product, A - productivity, K - capital, L - labor\ (L_d - demand, L_s - supply), I - regional\ infrastructure, \alpha - return\ to\ capital, \beta - return\ to\ capital, \gamma - \text{return to infrastructure}$$

(9) $\pi_t = P_{x,t} \cdot X_t - C(X_t) \rightarrow \pi_t = P_{x,t} \cdot A_t \cdot K_t{}^{\alpha} \cdot L_t{}^{\beta} - W_t \cdot L_t - R_t \cdot K_t$

$$\pi - profit, P_x - general\ product\ cost, C(X) - Costs\ for\ producing\ X, W - wage,$$

The firms seek to maximize profit, under which condition:

(10) $\frac{\partial \pi}{\partial L_t} = 0 \rightarrow \frac{\partial \pi}{\partial L_t} = P_{x,t} \cdot A_t \cdot K_t{}^{\alpha} \cdot I^{\gamma} \cdot \beta L_t{}^{\beta-1} - W = 0 \rightarrow L_{d,t} = \sqrt[1-\beta]{\frac{P_x \cdot A_t \cdot K_t{}^{\alpha} \cdot I^{\gamma}}{\beta \cdot W_t}}$

The produced product's price is designated as numeraire, hence, $P_x = 1$, so all wages are real wages. This yields a classical result of the demand for labor.

In order to explore the immediate employment effects of the earthquake on demand for labor, we denote t=1 for the time period prior to the earthquake and t=2 for the subsequent period. It is also assumed that during this period, wages are completely rigid, and set at W_1 .

It is therefore possible to describe the markdown of demand for labor as:

(11) $\frac{L_{d,2}}{L_{d,1}} = \frac{\sqrt[1-\beta]{\frac{A_2 \cdot K_2{}^{\alpha} \cdot I_2{}^{\gamma}}{\beta \cdot W_1}}}{\sqrt[1-\beta]{\frac{A_1 \cdot K_1{}^{\alpha} \cdot I_1^{\gamma}}{\beta \cdot W_1}}} = \sqrt[1-\beta]{\left(\frac{A_2}{A_1}\right) \cdot \left(\frac{K_2}{K_1}\right)^{\alpha} \cdot \left(\frac{I_2}{I_1}\right)^{\gamma}}$

Seeking to translate the demand for labor into labor output, it is first pertinent to factor-in a possible increase in search and matching difficulties for potential employees and employers. The existence of short-term, yet constant, unemployment due to a lack of matching has been long established (Pissarides 1985, Sahin et al 2014). However, it is not known whether this phenomenon increases in the wake of a disruptive event such as an earthquake.

Denote $0 < \delta(I) < 1$ as the ratio of employees failing to find jobs, even though there are employers seeking to hire at that wage. Note that it is possible that this ratio is dependent on regional infrastructure. We can therefore translate the demand for labor into actual labor output as the labor utilized under certain demand circumstances:

$$(12)\ L_{d,1} = \delta(I_1)\cdot L_{s,1}, L_{d,2} = \delta(I_2)\cdot L_{s,2} \rightarrow \frac{L_2}{L_1} = \frac{\delta(I_2)}{\delta(I_1)}\cdot \sqrt[1-\beta]{\left(\frac{A_2}{A_1}\right)\cdot\left(\frac{K_2}{K_1}\right)^{\alpha}\cdot\left(\frac{I_2}{I_1}\right)^{\gamma}}$$

Analyzing this expression, one can delineate the relationship between capital destruction, and subsequent immediate unemployment. Positing that technological productivity, A, does not change, the following represents the shape of immediate unemployment generated due to capital destruction, for a given α, β, γ.

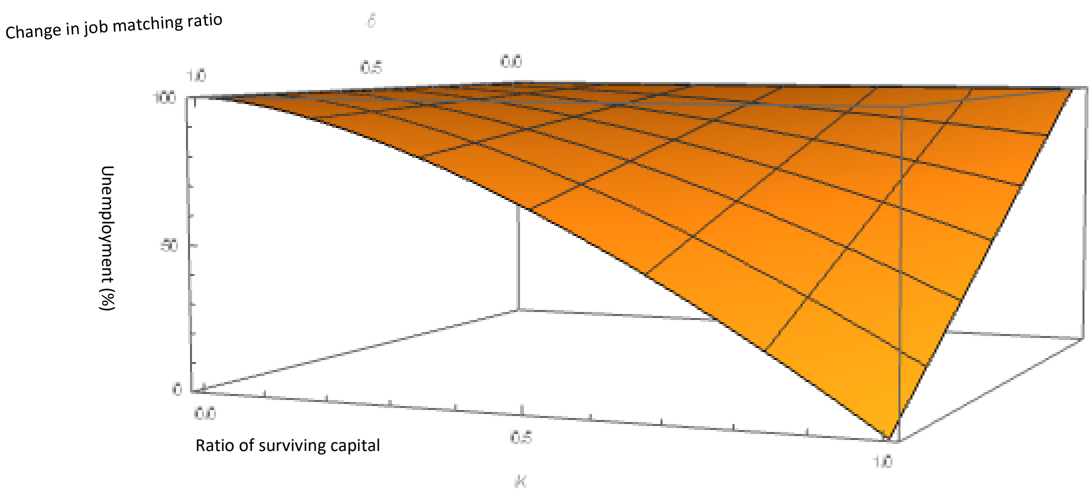


Figure 6 – unemployment (%) generated through a sudden reduction in capital (ratio), **α = 0.6, β = 0.45, γ = 0.25**

Figure 6 shows the result of numerical simulation of the extent of the effect of a sudden reduction in capital (such as that caused by a disaster) on unemployment. It is worth noting that the shape of this relationship is determined by the return to scale of the production function. That is, if the return to scale, $\alpha + \boldsymbol{\beta} + \boldsymbol{\gamma}$>1 then the effects of capital change on employment is concave, and if $\alpha + \beta + \boldsymbol{\gamma}$ <1 it is convex. If there is no return to scale then the relationship is linear**.** Figure 7 illustrates the simulated effect of returns to scale on unemployment. This relationship suggests that an industry's reaction to a decline in capital would correlate strongly with its return to scale. This potentially creates variance in results across regions, given the variation in the concentration of different industries in their labor markets.

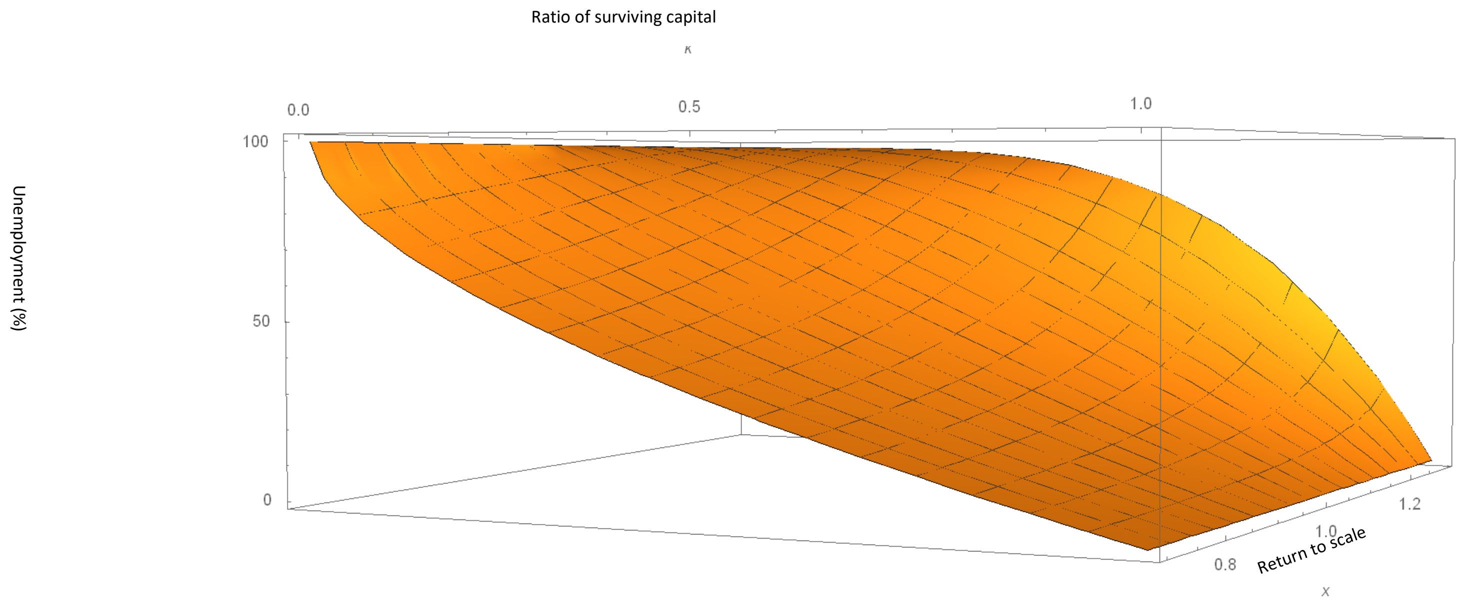


Figure 7 – effects of return to scale on unemployment, ratio of δ **= 1, α = 0.6**

4.2 Labor Supply

Individual decisions of workers exchanging time for earnings govern the supply of labor. . We use a 'reservation wage' setting, assuming that for each individual, *i*, income and substitution effects cancel out until a certain wage ω_i (the natural logarithm of wages), from which point individuals are willing to work. This represents participation in the job market and the equivalent of a full-time position.

The variable ω_i must be heterogeneous across individuals. For simplicity, we assume that $\omega_1$is normally distributed amongst the population, with a mean of $\overline{\omega}$ and a standard deviation of ${\sigma_\omega}^2$:

$$\omega_i \sim Norm(\overline{\omega}, {\sigma_\omega}^2)$$

Therefore, workforce participation rate would equal $\phi(\frac{\omega-\overline{\omega}}{\sigma_\omega})^{-1}$ for the population from which this distribution was drawn.[8] Denoting its size as P, total workforce would be

[8] $\phi(\frac{\omega-\overline{\omega}}{\sigma_\omega})^{-1} \leq 1$ by definition, as it is a cumulative distribution function

(13) $P \cdot \phi\left(\frac{\omega-\bar{\omega}}{\sigma_{\omega}}\right)^{-1}$ $[workers]$

(14) $Log(W_t) = \mathrm{Log}(\mathrm{W}_{\mathrm{t-1}}) + e \cdot Log\left(\frac{W_{t-1}^{*}}{W_{t-1}}\right)$

This would mean that the supply of labor, for a given $\bar{\omega}$ and ${\sigma_{\omega}}^2$ is of the following form:

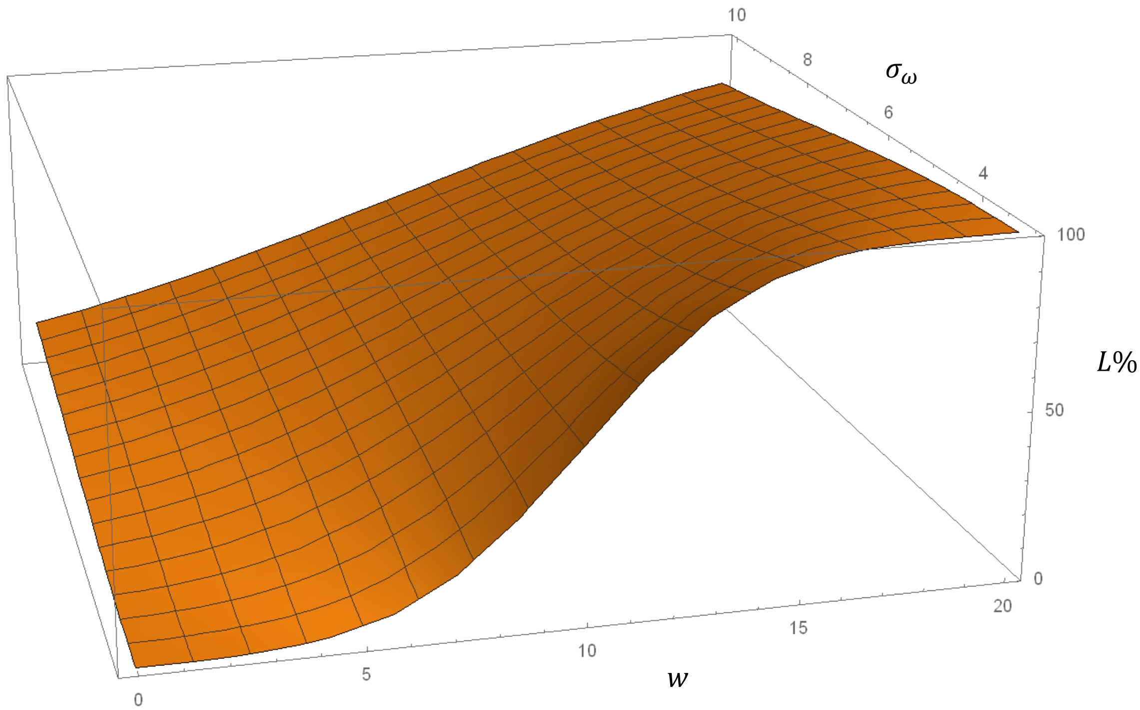


Figure 8. The relation between wages and labor offered, for $\bar{\omega} = 10$

Figure 8 illustrates a well-behaved labor supply curve that tends to homogenization with increase in $\sigma^{2.}$ Using this result for the supply of labor for a given set of parameters, we can simulate a theoretical equilibrium of wages (Fig. 9).

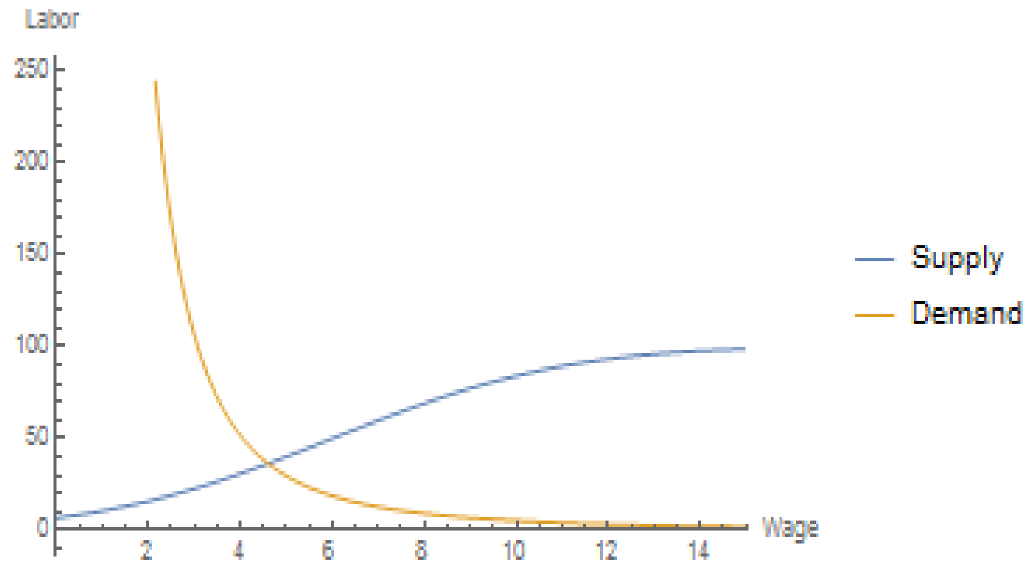


Figure 9. Labor market equilibrium for a given set of parameters: $\sigma_\omega = 4, \bar{\omega} = 6, P = 100, K = 50, I = 35, \alpha = 0.4, \beta = 0.6, \gamma = 0.25, A = 1$

4.3 Medium Term Dynamics: Gradual flexing of wages

The temporal change in wages is a well-researched topic within the labor economics literature (Hall 2005a,b). One popular way of thinking about wage changes is that of price rigidities – producers and consumers (in this case employees and employers) do not bid freely for labor. Rather, they are subject to certain constraints which might relax over time. Classically, if frictions were not present, we would expect employees and employers to clear the market quickly, by adjusting the price of labor to the equilibrium wage. Final labor offered and utilized is determined according to this wage and no unemployment ensues. Simply this relation can be stated as:

(15) $\log(W_t) = \log\left(W_t^{\circ}(K_t, I_t)\right)$

Where W_t denotes the wage at time *t* and $W_t^{\circ}(K_t, I_t)$ the market-clearing wage. However, friction introduces a temporal adjustment process in which agents in the marketplace observe current market conditions (i.e. the level of capital) and so are able to determine the market clearing wage, but are unable to immediately adjust wages accordingly. In the following model, the amount by which agents may change the wage is relative. That is, wages are ordinal, and friction is relative. For example, a change of wages from $1,000 to $3,000 is much 'harder' to make, than a change from \$100,000 to \$103,000, but 'should be' as hard as a transition from \$100,000 to \$300,000. This is popularly captured by the elasticity property; in this case, the elasticity of wages to relative change. In our simulation we model this temporal process using what we term as the 'temporal wage adjustment equation':

(16) $\log(W_t) = \log(W_{t-1}) + e \cdot \log(\frac{W^{\circ}}{W_{t-1}})$

Where $e_{W^{\circ}}$ denotes elasticity of change in relative wages. Note that if we were to multiply all wages by a constant factor, the temporal change would be unaffected. The temporal wage adjustment equation can be rewritten as:

(17) $\log(W_t) = \log(W_{t-1}^{1-e}) + \log(W^{\circ e})$

The new wage is therefore made up of two components: a) the new equilibrium wage, and b) the previous wage. The elasticity to change serves as a 'weight' to each of these components. Using this formulation, it is easy to see that when the elasticity to change is 1, that is each 1% of 'wanted change' is translated to 'actual change', then we revert to the classical market clearing equilibrium.

5. The Post Disaster Labor Market Dynamics- Some Scenarios

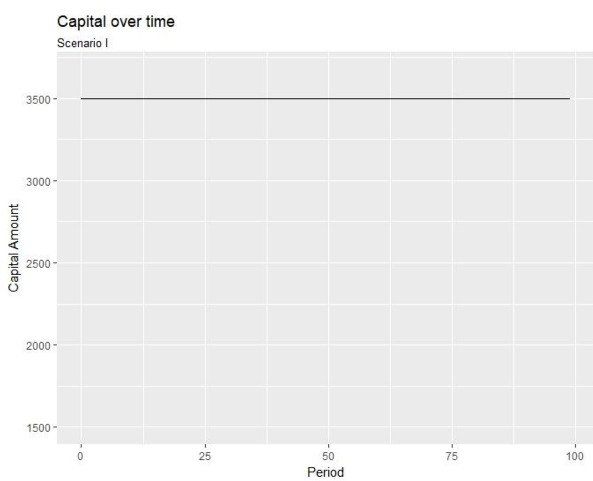
In the following section we use the temporal wage adjustment equation to demonstrate how three recovery scenarios play out in the labor market. Initially, we present the results of a no-disaster scenario to demonstrate the properties of the model and visualize its results. The next two scenarios describe various specifications of the model, in which a disaster strikes at a certain point. The disaster's occurrence is not stochastic, but rather preset. All agents regard the change of such a disaster to be zero, at all times, so its realization does not affect their underlying behavior or expectations. In all simulations initial capital is set to 3,500, matching friction is constant and set at 4% and $\omega_i \sim Norm(17,7)$. Additionally, for simplicity infrastructure is left out at this stage. Using these parameters, equilibrium wage is exactly 22.6, and participation rate is approximately 75.66%. Throughout all simulations, the elasticity of change in relative wages, denoted e above has been set to 0.3 – meaning wages adjust by 30% of what they would have without friction.

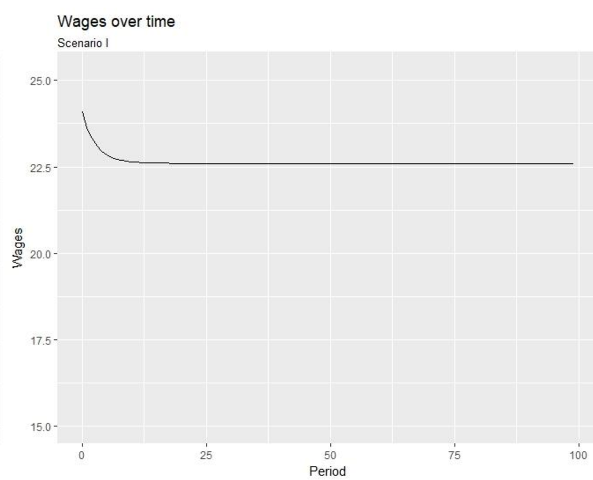
Scenario I

This scenario demonstrates the basic variables tested and reported. Four variables are plotted in Fig 10: capital stock, wages, labor participation rates and the unemployment rate. The relationships between the variables are as described in the previous sections. In each iteration, meaning in each period, wages are set as a compromise between the last iteration's actual wage and equilibrium wage. Using this new wage, labor supplied and demanded is derived, the minimum of which is taken as actual utilized labor. This amount of labor is then used to calculate the would-be equilibrium wage of this period.

In this scenario initial wage is positively offset by 6.63% from the equilibrium wage. There is no change in capital throughout the simulation, and so all changes are due to this single 'shock' to wages. Despite the seemingly modest offset to the equilibrium wage, the resulting unemployment is significant. High wages cause an oversupply of labor as more workers are induced to the marketplace than are demanded. This oversupply results in 21.8% of jobs seekers not finding a job but by the fifth period wages revert to equilibrium-level and unemployment returns to the natural 4% rate caused by matching friction.

The high initial unemployment is largely due to the impact wages have on employers. In an economy where capital is completely rigid and there are no stockpiles, employers react very strongly to wages. However, this unemployment is largely canceled out by the 8th period, as both participation rates and wages fall. Note that wages reach their equilibrium level in tandem with the clearing of unemployment.





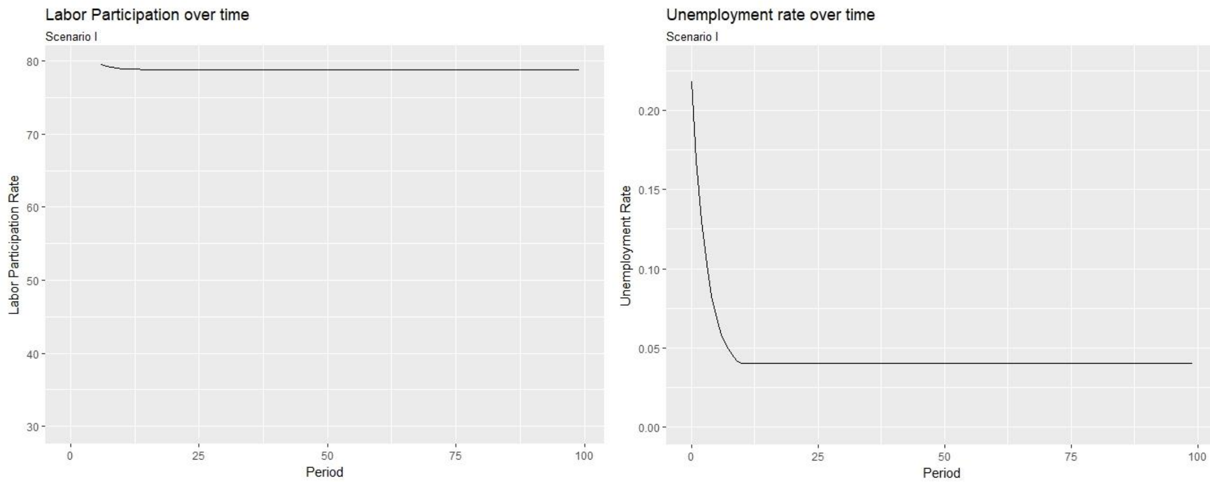


Fig 10: Shock to Wages, no disaster

Scenario II

Scenario II is a basic disaster scenario. Capital grows at a rate of 0.4% per period, without changes to reservation wages, as is evident by the early growth in participation rates. Disaster strikes at period 30, destroying 45% of available capital (Fig 11). This event is followed by 15 periods of 'reconstruction', or rapid growth in capital, of 1.5% per period. After this temporary reconstruction a 0.4% equilibrium-level growth in capital is resumed.

The initial unemployment is dramatic – reaching over 50% in the immediate post-disaster period. This however, is unsurprising. As stated above, the returns to labor and capital are equal in all scenarios and so a "disappearance" of almost half the capital would translate to roughly half the jobs disappearing, with a minor attenuation caused by other elements in the model. However, this unemployment is brief, since wages plummet as employers put significant pressure on wages to adjust downwards.

What follows can be divided into three distinct time frames. The first starts with the disaster, and ends at the nadir of wages. This low-point is also, not coincidentally, the point at which unemployment returns to natural levels, of 4%. During this timeframe the labor market is filled with slack – available but under-occupied labor. This slack allows employers to lower wages relatively quickly thus permitting them to quickly rehire, despite worker's lower productivity. This dynamic is very different to capital-driven change, which is more evident in the second and third time frames.

The second timeframe is characterized by rapid growth in capital and wages. As all slack is cleared from the market, total labor growth stalls. Instead, it resumes in a convex relation for both wages and labor. This timeframe is relatively brief, but it exposes a second ‘slack’ in the market, that of businesses still eager to hire due to the brisk pace of recovery. Demand outstrips supply, and wages quickly rise. However, due to the shape of the supply distribution the marginal increase in the supply of labor declines as more people join the labor market, thus making it more costly to induce more potential employees to join the market. The convex relationship quickly gives way to a concave one, meaning a slowing pace of growth. Even before the recovery period ends, the rate of growth is already smaller. Friction in wages causes this relationship to continue even past the ‘end of recovery’ phase. Not all new capital is transformed to new labor. It would appear that the second timeframe does not end until the 50th period, five periods after capital accumulation reverts to its natural 0.4% rate.

Finally, the third period is the return to the equilibrium state. Wages grow linearly mirroring the growth in capital. Labor rises in tandem, and the variables return to their pre-disaster levels at approximately the 90th period. This simulation exposes the myriad of market dynamics that can be generated by a sharp decline to capital. At its core the market is driven by interaction between capital recovery and the shape of the supply curve, and is mediated by the wage friction.

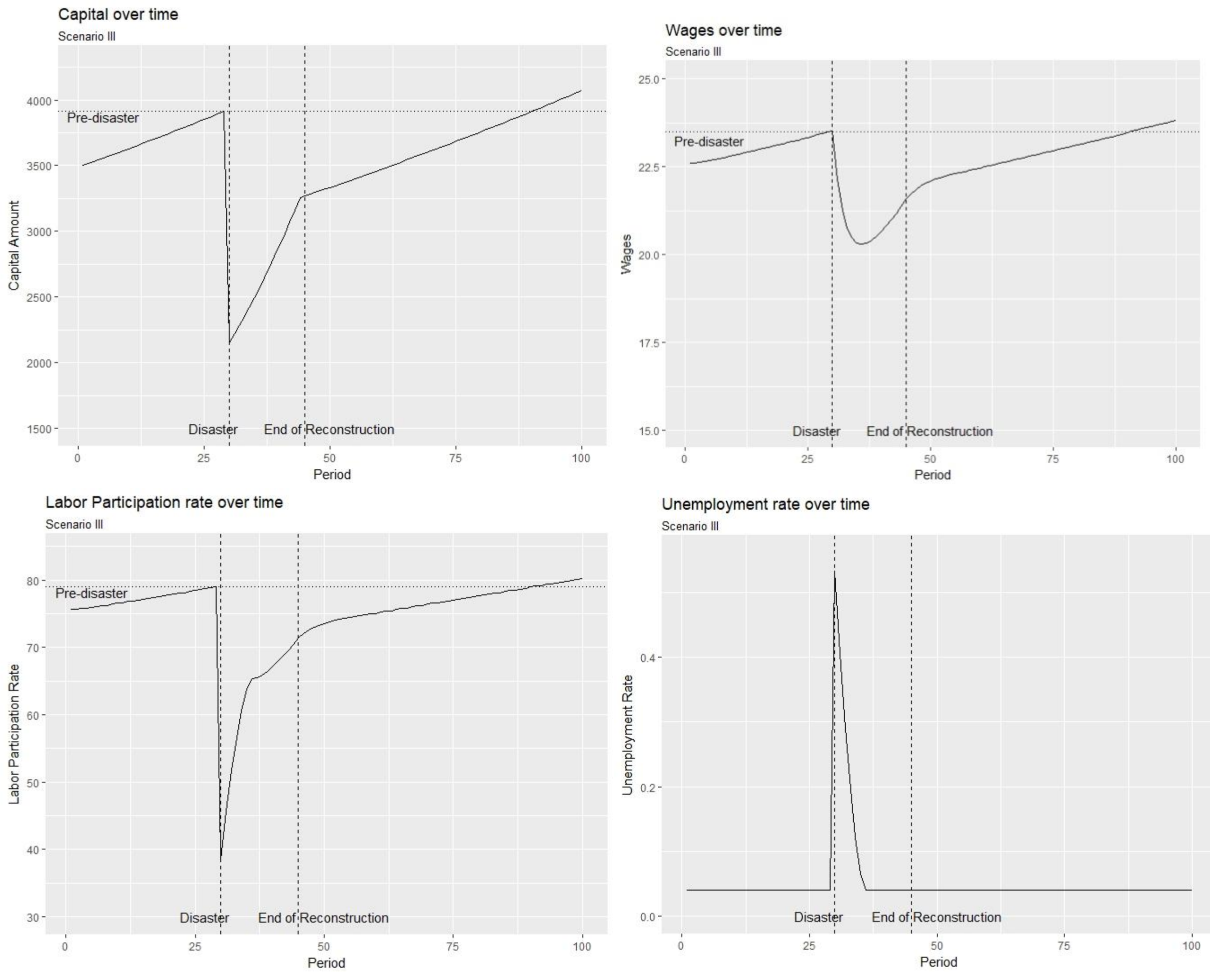


Fig 11: Basic Disaster Scenario

Scenario III

This scenario introduces a simple endogenous emigration model. In this model, regional population follows gaps between the supply and demand for workers. People emigrate when there is an oversupply of labor and immigrate when the opposite occurs. All such individuals are drawn from the same reservation wage distribution.

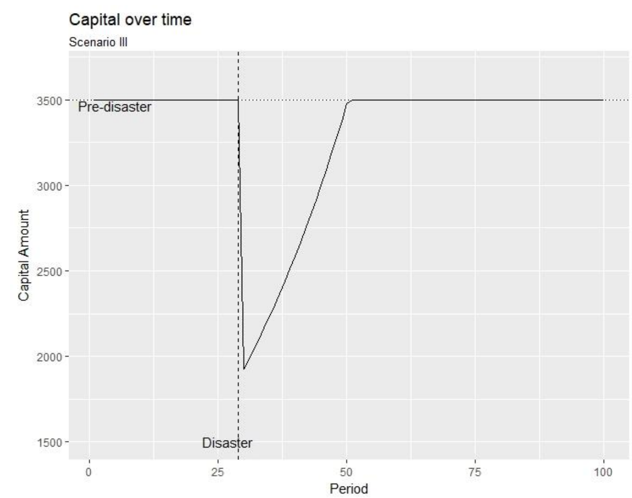
$$P_t = P_{t-1} + \theta \cdot (L_d - L_s)$$

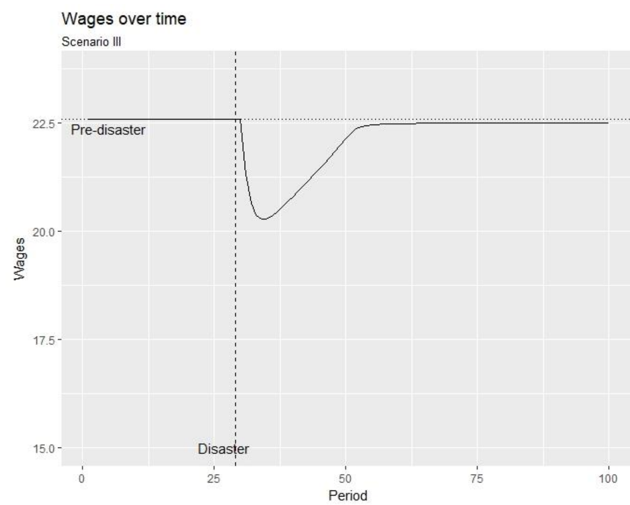
Scenario III (Fig. 12) specifies that in each iteration, a quarter of the gap between labor supply and demand is translated to population movements, and so $\theta = 0.25$. θ is 'spatial friction' for individuals, and its value is obviously arbitrary, set exogenously only to serve as a model parameter. In reality, it is likely correlated with other labor market aspects. Note that emigration due to employment availability, rather than maximization of wages makes this model comparable to the AB simulation presented above. However, unlike the AB model, individuals do not commute to out of region jobs, but rather move out.

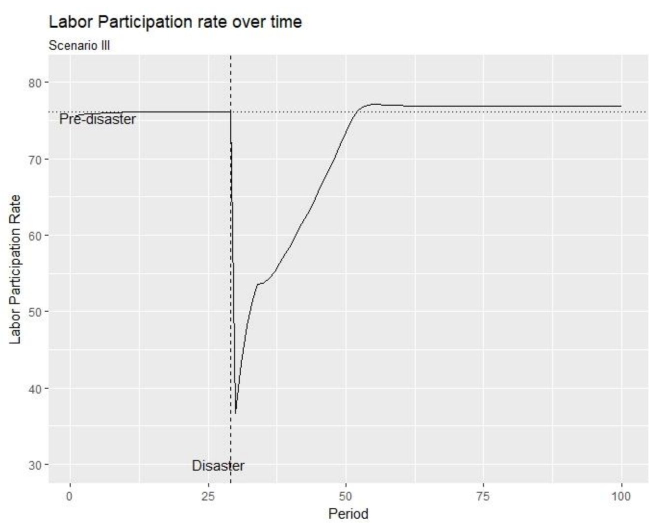
Following the disaster at t=30 and the labor surplus induced by the disaster of the market, people quickly emigrate out of the region. Population reaches a minimum of 82% of initial population at time t=33. Also at t=30 unemployment clears, following a peak of 53%. The market clears sooner in this case than in scenario II, and with a minimal wage, for obvious reasons – part of the extra slack in the market is absorbed by the supply shrinking directly. These are unsurprising results given the construction of immigration.

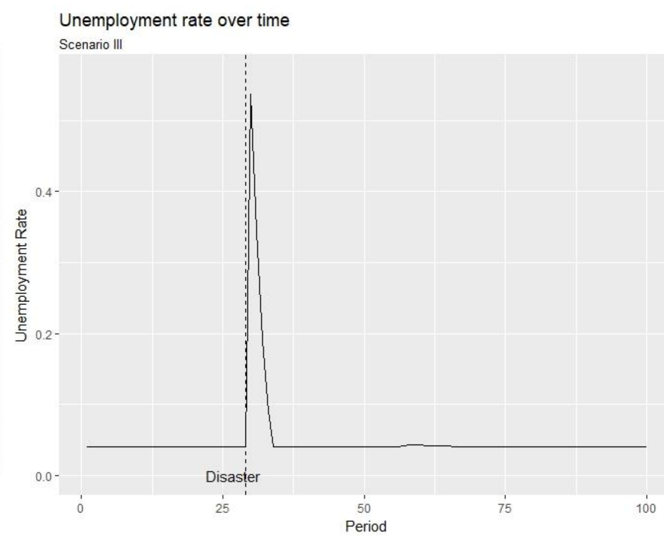
Similarly to scenario II what follows is a process of access demand in the market, as businesses seek to exploit rising capital levels and rehire individuals. Rising wages induce the remaining population back to the market, but within a few periods the existing slack is cleared, and rising participation restarts at a slower pace – brought forth by rising wages. The same demand also causes immigration and at period 50 population returns to 100.

Interestingly, the population continues to grow. Although capital reconstruction has ceased, there remains excess demand in the market, which is absorbed by an increase to the number of employees. That is, supply continues to increase, not by moving further to the right of the reservation wage distribution, but rather due to an increase in the absolute number of regional workers willing to work at any given wage. This results in a permanent increase to population. At the 100^{th} period, population is 2.2% higher. Businesses can fill positions, obviating the need to raise wages all the way to their pre-equilibrium levels. At the end of the simulation, wages are 0.44% lower.


Capital over time
Scenario III
Pre-disaster
Disaster
Capital Amount
Period
3500
3000
2500
2000
1500
0
25
50
75
100


Wages over time
Scenario III
Pre-disaster
Disaster
Wages
Period
22.5
20.0
17.5
15.0
0
25
50
75
100


Labor Participation rate over time
Scenario III
Pre-disaster
Disaster
Labor Participation Rate
Period
80
70
60
50
40
30
0
25
50
75
100


Unemployment rate over time
Scenario III
Disaster
Unemployment Rate
Period
0.4
0.2
0.0
0
25
50
75
100

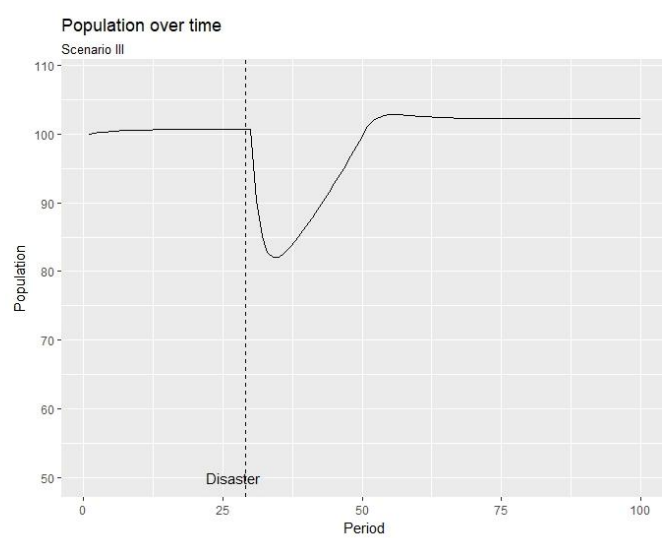

Population over time
Scenario III
Disaster
Population
Period
110
100
90
80
70
60
50
0
25
50
75
100

Fig 12: Disaster Scenario with Migration

The results of this simulation demonstrate on the one hand, the attenuation that population changes have on labor market dynamics and the long-lasting effects on local equilibrium from changes in labor supply, on the other. These changes are made possible by an opening in the labor market, allowing not for the exchange of labor directly, but rather of its factors of production.

6. Conclusion

The aim of this paper is to explore the possible long-term implications of an urban disaster for the labor market. This is achieved by considering two opposing conceptualizations of the urban labor market and simulating them using appropriate frameworks. The first approach treats labor as tradable and products as rigid. This means that workers are able to move in and out of the region and that firms are entirely dependent on local demand. The dynamics of this system are simulated using an agent-based model that considers the interactions between the labor market, housing market and the land-use system within the real-world environment of Jerusalem's city center. The reverse approach treats labor as immobile and products as tradable and is simulated using a more traditional micro-economic framework.

When no physical shock is introduced into the system, some similarities can be seen between the results. Measures such as labor participation rates and regional average wage decline over time and low-level equilibrium values emerge. Yet, under the rigid-labor approach, a temporary change in the wage still clears the market quickly, while in the AB approach changes are resolved much more gradually. This is the natural result of the different conceptualizations of the system. In the micro-economic approach a solution to the slack is found within the system, thus pushing for rapid convergence. In the AB system unemployed workers search for jobs solutions outside the area. When a disaster is introduced into the system these differences become accentuated. As firms offer products that are only consumed locally within the AB model, they are limited in their ability to sustain the shock. They then go out of business, by being replaced by other (residential) land-uses. In response to declining demand workers find themselves pushed to find solutions outside of the area, meaning that employment rates stay high, but local employment plummets. A reorganization of the system under the rigid labor conditions only appears when population mobility is introduced into the system. The first disaster scenario just leads to the system returning to its pre-shock growth path with workers absorbing the reconstruction process. The second which includes population movements, leads to a new equilibrium state.

The results of these two implementations serve to highlight the importance of mobility and flexibility in determining the long-term outcomes of a disaster. In its absence, it seems that systems would simply bounce back, but when mobility, or lack thereof, is considered a tendency to reorganize seems to emerge. How the system reorganizes is related to the kinds of mobility considered. The two examples here produce very different results that point to other implications. The economic literature favors the tradeable products approach while the mobile labor approach yields a more comprehensive approach to urban rejuvenation when applied within an appropriate agent-based framework. As no system is totally mobile in one manner and entirely rigid in another, the two approaches ideally need to be integrated.

Another important difference between the cases considered in this paper is that of absorption. While we did not consider the direct cost of capital recovery, these results indicate that the recovery process has additional costs that are shared unevenly within the market. In both cases, agents that are rigid are forced to absorb the readjustment process. In the AB model, most commercial land-use shifts to residential land use. As land use serves as a proxy for firms, local businesses appear to leave the market. Their workers, being mobile, simply find jobs outside. Strikingly, the opposite occurs under the second framework. Firms readjust their demand for labor, and are able, though slowly, to affect the wages they pay. All firms that are able to withstand this initial part survive, as after the nadir point of wages, labor demand grows continuously. Instead, workers are forced to absorb unemployment, followed by a prolonged period of reduced wages and participation. The final wage bill is thus much smaller. These divergent 'absorption costs' should also be considered a key factor in the recovery process. The relative rigidities and spatial friction of the local industries, and of the local labor market, thus have the potential to widely effect the human and economic costs of the recovery period.

The juxtaposition of our two extreme frameworks is by design. It is intended to highlight the fundamental divergence that relative rigidities and spatial frictions can introduce. These underscore the importance of characterizing the local nature of the urban system and in particular, the role of inputs and interactions between local systems and the outside world. The mobility of workers, population and products within these systems guides the urban rejuvenation process. An incomplete understanding of these rigidities and constraints on mobility can lead to unrealistic expectations of recovery.

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Appendix 1: Definitions

Definitions

Individuals are the basic agents of the system. Each agent is assigned to a household defining another set of agents. Households also hold unique attributes which lower-level individual agents inherit such as place of residence and car ownership. These two entities are mobile and initiate actions by themselves. The model also includes several immobile quasi-agent entities such as jobs, buildings and roads. Each of these agents is assigned multiple definitive traits.

Definition 1 (Agent): an individual agent *a* is represented by the tuple $(id_a,hh_a,d_a,age_a,wf_a,job_a,I_{exp,a},I_{real,a},S_a,P_a)$

where: *id* is a unique ID, *hh* is the ID of *a*'s household, *d* indicates whether *a* is disabled in any way, *age* is the age group of *a* (child, adult, elderly), *wf* indicates whether *a* is a member of the workforce (can be true only for adults and elderlies), *job* is the id of *a*'s workplace (none if unemployed, or zero if *a* commutes out of the study area), I_{exp} is the minimal monthly wage *a* expects to receive for a full-time position, I_{real} is the actual wage *a* receives (if *a* is employed within the area, this is equal to *job*'s wage), *S* is the number of days *a* seeks a job.

Definition 2 (Household): a household agent *h* is represented by the tuple $(id_h,b_h,car_h,i_h,m\_age_h,P_h)$

where: *id* is a unique ID, *b* is the ID of *h*'s residence building, *car* indicates whether *h* owns a private vehicle, *i* is the total income for *h*'s members, *m_age* is the mean age group for *h*'s members, *P is h*'s housing preference score.

Definition 3 (job): a job entity *j* is represented by the tuple (id_j,w_j,b_j)

where: *id* is a unique ID, *w* is the wage offered for this position, *b* is the ID of *j*'s building.

Definition 4 (building): a building entity *b* is represented by the tuple $(id_b, lu_b, floor_b,fs_b,xy_b,ap_b,rent_b,u_b)$

where: *id* is a unique ID, *lu* is *b*'s land-use, *floor* is *b*'s number of floors, *fs* is *b*'s floor-space volume, *xy* indicates *b*'s location (i.e. coordinates), *ap* is the number of apartments (real or potential) within *b*, *rent* is the monthly cost of living in an apartment in *b*, *u* is a binary variable indicating whether *b* is usable.

Definition 5 (road)[9]: a road entity *r* is represented by the tuple $(id_r,xy_{b,r},xy_{e,r},l_r,traf_r,a\_traf_r,f_r)$

[9] This definition includes the necessary information for producing a network-based spatial representation of the road network with relative ease.

where: *id* is a unique ID, xy_b are *r*'s start point coordinates, xy_e are *r*'s end point coordinates, *l* is *r*'s length, *traf* is the momentary traffic volume on *r*, *a_traf* is a list of the values of *traf* over a given temporal range, *f* indicates whether *r* is usable.

Definition 6 (LHM): a LHM entity *c* is described by the tuple (p_c,m_prob_c,hp_c)

where: *p* is a description of *c*'s geometry (e.g. list of coordinates), *m_prob* is the daily probability for a household residing in *c* to migrate to another LHM, *hp* is the average housing price per meter in *c*.

Appendix 2: Data Sources and Parameter Values

Various global parameters are required for different components of the framework, as detailed in Table A1. These detailed definitions and parameters mean that a substantial amount of information is needed to run the model. We derive most of these empirically for our case study.

Parameter	Type	Sub-model(s)	Description	Value in case study	Source
Out_prob	float	Residential location	Chance for a household to migrate out of the study area; Ranges from 0 to 1.	0.000029	Central Bureau of Statistics (CBS), 2016
In_comm	float	Residential location, land-use	Chance for a job to be occupied by a worker residing outside of the study area. Ranges from 0 to 1.	Set after the initialization of the simulation to be the share of jobs occupied by in-commuters out of all jobs	Endogenous
N	float	House pricing	Used to normalize the translation of buildings values to monthly rents	1/3	Arbitrary
in_mig	float	In migration	Used to determine the number of in-migrating households	0.54427	Based on the ratio between in-migration and out-migration for the study area (CBS, 2016)
σ_{in_mig}	float	In migration	Used to determine the number of in-migrating households	0.45573	Arbitrary (=1-in_mig)
ActNum	integer	Activities location	Represents the average number of activities per agent	3	Arbitrary
ω_{act}	float	Activities location	A weight parameter for different mobility-related variables	1/3	Arbitrary
ω_{n}	float	Activities location	A weight parameter for the 'riskiness' of an area	1/3	Arbitrary
ω_{d}	float	Activities location	A weight parameter for travel distance	1/3	Arbitrary
ω_{fs}	float	Activities location	A weight parameter for floor-space volume	1/3	Arbitrary
$job\_dens_{residential}$	float	Land-use	Indicates the number of jobs per square meter, for residential uses	0.00047	Computed by integrating floor-space and job numbers per spatial unit data (Source: CBS, 2016)
$job\_dens_{commercial}$	Float	Land-use	Indicates the number of jobs per square meter, for commercial uses	0.03151	

job_dens_{public}	float	Land-use	Indicates the number of jobs per square meter, for public uses	0.04795	
a_wage	float	Land-use, Wages	Average offered wage	7177.493	Computed endogenously, based on input data
σ_{a_wage}	float	Land-use, wages	SD value for offered wage	1624.297	Computed endogenously, based on input data
α	float	Wages	Capital stock power parameter	0.75	Arbitrary
β	float	Wages	Wage power parameter	0.75	
$\omega_{d,j}$	float	Workplace location	A weight parameter for commuting distance in workplace location preferences	0.5	Arbitrary
SL	float	Workplace location	Median length of job search	30	Arbitrary
θ	float	Shock	Shock intensity	1	Arbitrary
q	float	Shock	Normalization factor	1380	Arbitrary, set to constrain the shock
recon	float	Shock	Reconstruction speed parameter	5	Arbitrary, set to allow for a reasonable recovery pace

Table A1: Model parameters.

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