Modeling industrial symbiotic processes from a complex systems perspective

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ABSTRACT

The 'circular economy' is recent approach on questions of sustainability. An important concept within the circular economy is industrial symbioses. Industrial symbioses is about creating an integrated byproduct and waste cycle between industrial actors.These so called 'closing the loop' mechanisms are aimed at maximizing economic value and minimizing environmental effects. The idea of these mechanisms corresponds to complex system paradigms, however complexity science has hardly been utilized in this field. In this *working paper* we describe a toy model to model waste flow between actors on the level of organizations/businesses. Its purpose is to investigate how waste flow is affected by different parameters such as, distance, clustering, transportation cost and other parameters. In this paper we explain the rationale of the basic model, present some exploration of the model and we present some preliminary results. Future developments will include the application to real world spatial maps and infrastructures, and calibration to data of first real-world implementations of 'circular economy practices'. The goal is to make a basis for an open source circular economy application that can be used to monitor the circular economy, as well as create a market place for waste products.

Introduction

Towards a Circular Economy

Concept

The 'circular economy' is recent approach on questions of sustainability. The current 'take, make, waste' way of producing is considered to be not sustainable anymore. Current thoughts on 'closing the loop' mechanisms on producing and consuming are booming in many different academic fields. An important concept within the circular economy is 'industrial symbioses'. The main idea of industrial symbioses is that traditionally separate industries act collectively to obtain a mutual competitive advantage through their physical exchanges of materials, energy, water, and byproducts and thereby creating an environmental advantage as well [1]. The industrial symbioses approach seeks to recycle residual waste or by-products through the development of complex interlinkages between companies and firms. In direct contrast with the conventional linear economic approach of material production of produce-use-dispose, the circular economy concept seeks to reduce the uptake of virgin materials while also reducing total waste production by accommodating the cycle of materials. This concept is distinct from traditional recycling whereby products are often reduced to their lowest nutrient level, and then disposed of. In a circular economy approach, waste or by product materials of one firm have the potential to become high nutrient level inputs to another firm. As a result, there isn't a sequential downgrading of waste or by-products, but rather a full cycling of materials.

A crucial factor in industrial symbiotic processes is the geographical proximity of the different industrial actors. Industrial symbioses is about the physical exchange of waste/byproducts. In order to efficiently exchange byproducts an industrial actor often has to look for the symbiotic possibilities in its direct geographical proximity. Think for instance of excess heat. It is harder to keep excess heat the same temperature the further it needs to be transferred. So symbiotic activities and optimizing waste flows will most likely be more successful if the industrial actors are near each other. Eco-industrial parks are often considered concrete realizations of the concept industrial symbioses. On these parks businesses work together to reduce waste and pollution and effectiveness share different kind of resources and exchange byproducts. The key advantage is that these actors are located together and therefore exchanges and infrastructure are easier realized. However, these parks are often far from being self sufficient. In order to optimize 'waste' flows parks need to exchange with actors from different parks/geographical areas as well. This makes optimizing waste flow and 'Closing the loop' mechanisms a highly complex phenomenon, with actors on different levels and on different geographical distances.

So 'closing the loop' mechanisms in industrial symbiotic exchanges have a clear spatial component. However, the role of this spatial component has never been formally researched. While many large organizations, including the EU and the UN, have expressed interest in adopting the a circular economy approach, much work which has been done has either focused on small scale applied examples or on theoretical frameworks and models. As such, studies are needed which seek to model the dynamics of the circular economy concept, and begin to offer larger more generalized examples of how the concept feasibly be achieved. We propose thus in this working paper to tackle this issue at a modest level, by exploring patterns of theoretical feasibility from an agent-based modeling point of view. It has been recently postulated that evidence-based methods, in particular agent-based modeling, could be crucial for economy in general[2]. In this paper we study the effect of different geographical concepts on the the functioning of a symbiotic system as a whole, by means of an agent based model. In this model actors are located on a spatial plane. Each actor has an input and an output in terms of needs and waste. The goal of the agents is to minimize the waste and maximize there economical profit. First we study whether there is a spatial effect on the functioning of the system by comparing a uniform spatial distribution with a theoretical real world distribution and a empirical distribution. Secondly, we study the effect of geographically matching the actors on there input and output on the functioning of the system. In what follows we'll present a working paper in which we explain the rationale of the basic model, present some exploration of the model and we present some preliminary results.

Methods

Rationale

Model Core

Model setup The core part of the model is assumed to take place at a single scale, but with variable spatial range. The agents are N companies indexed by $1 \leq i \leq N$, that have a fixed spatial position $\vec{x}_i$. In order to focus on the exchange of by-products as inputs for other companies, we choose not to model the effective product nor the "external" inputs. For the sake of simplicity, by-products are assumed to be described by a finite-dimensional real variable $\vec{y} \in \mathbb{R}^d$. Finite values are a reasonable domain for by-products characteristics as it allows to normalize along each axis and take $\vec{y} \in [0,1]^d$. Each company has a demand function and an offer function, which were used to establish links between pairs of companies (i.e. exchange of by-products). These function are defined in a simple manner by $\vec{D}_i(\vec{y}) = D_i^{(0)} \cdot \vec{d}_i(\vec{y})$ and $\vec{O}_i(\vec{y}) = O_i^{(0)} \cdot \vec{o}_i(\vec{y})$, where $\vec{d}_i$ and $\vec{o}_i$ are multivariate probability densities. We started our simulation with a set of companies that were not linked with each other, and then grew the network based on rules determining exchange of by-products (effectively creating links between companies).

Growing the circular economy network The temporal scope of the model evolution was assumed to be at a mesoscopic time scale, following the assumption that companies localization and the surrounding urban environment (which includes the transportation cost landscape) remain constant. The temporal dynamics consist of network growth, i.e. the progressive establishment of complementary links between companies that correspond to flows of by-products.

Two factors were used to establish links between companies (i.e. exchange of by-products): 1) the geographical distance separating them, and 2) the match between demand and offer. The geographical interaction potential (V_{ij}; i.e. probability of two companies interacting based on their geographical location) decreased exponentially with distance such as $V_{ij} = \frac{1}{d_{ij}^{\alpha}}$ Increasing geographical distance also meant increasing transportation cost (in a linear fashion). The match between a company's offer (i.e. what it wastes after production) and another company's demand (i.e. what it could use for production) was computed along a "by-product" axis (an abstract by-product one-dimensional space, which could later be generalized to a multi-dimensional space). Along this by-product axis, the offer function and a demand function of each company are represented by a gaussian density distribution. We computed the overlap between pairs of demand and offer functions $o = \int min(O,D)dx$ – a higher overlap indicating a higher probability that the two companies exchange by-products – and used an overlap threshold T_o above which companies could potentially exchange by-products. This modeling approach was inspired by the ecological literature on probability niche models in complex food webs[3,4]. In these models, predation interaction between two species was modeled as the probability of species i eating another species j based on their values along a "niche" axis. More specifically, species i has a feeding optimum and the probability of eating species j declines has the niche position of species j gets further from this feeding optimum, which was model using a Gaussian centered on the feeding optimum.

The utility function associated with each potential exchange of by-products between two companies was defined as follows:

$$u = o - c \cdot \frac{d}{d_{max}}$$

where o is the overlap between the two companies in by-product space, c is the transportation cost, d is the geographical distance between the two companies, and d_{max} is the maximum distance between any two companies in the system.

In our model, at each time step, the following set of rules was applied:

- A company, the "current contractor" is drawn at random
- Potential partners are drawn
  - according to geographical interaction potential $V_{ij} = \frac{1}{d_{ij}^{\alpha}}$
  - among these, the ones whose overlap is above T_o are taken as potential partners
- given the set of utilities $(u_{1j}, u_{j1})_j \simeq (u_j)_j$, the potential partner with best utility is chosen

Indicators of Circularity The circularity of the model was evaluated using the method of Haas et al.[5]. The authors define the *degree of circularity* within an economy as recycling as a percentage of processed materials. *Processed materials* are defined as the sum of consumption of materials (input into the system) and recycled materials. The authors further define the indicator *waste throughput* as the waste output as a percentage of processed materials.

For a given model run with n companies and W total waste output, the three indicators can be calculated as follows (see Figure 1 for visual representation of variables):

1. Processed Materials (PM):

$$PM = IM + RM = n + (n - W)$$

where IM is the total material input (i.e., the number of companies n, given that each company requires one unit of input), and RM is the recycled materials (i.e., IM, or n, less total waste W).

2. Degree of Circularity (DC):

$$DC = \frac{RM}{PM} = \frac{RM}{IM + RM} = \frac{n - W}{n + (n - W)}$$

3. Waste Throughput (WT):

$$WT = \frac{W}{PM} = \frac{W}{n + (n - W)}$$

In their study,[5] estimate these indicators for the global and European economies. The authors found that the total processed materials in the global economy is 62 Gt/year (58 Gt/year raw material plus 4 Gt/year recycled), and the degree of circularity is 6 percent. The European Union was found to have 7.7 Gt/year of total processed materials with a degree of circularity of 13 percent. Waste throughput for both economies was found to be 66 percent. These real-economy values could provide a point of comparison for further development of the model that would include real world economic data.

Geographical setup The initial position of companies can be setup in many ways. The most basic case is a spatial uniform distribution of coordinates, and the model is first tested on it. A more refined spatialization can be done given a population density field $d(\vec{x})$. Assuming a local scaling of companies number as a function of population of a city N (not verified at a small scale, but more reasonable at a macroscopic scale), $Y \sim N^{\alpha}$, we take the probability for a firm to locate in a patch as a function of its population $\mathbb{P}(\vec{x}_i = \vec{x} | i) \propto \left(\frac{N(\vec{x}}{\sum N}\right)^{\alpha}$. Companies are thus located sequentially at random, given these probability. Population distribution can be synthetically generated, as a kernel mixture $P(\vec{x}) = \sum_{1 \leq j \leq p} K_j(\vec{x})$ with p number of cities (or "centers"), and kernels $K_j(\vec{x}) = \cdot \exp - \frac{||\vec{x} - \vec{x}_j||}{r_0}$ where x_j is random with uniform distribution and r_0 is computed such that the city system respects Zipf rank-size law with exponent γ (similar values at origin assume a constant maximal center density across cities), i.e. such that $P_j = \iint K_j \propto \frac{1}{j^{\gamma}}$. For real system, we use the raster population density with 1km resolution from CIESIN[6].

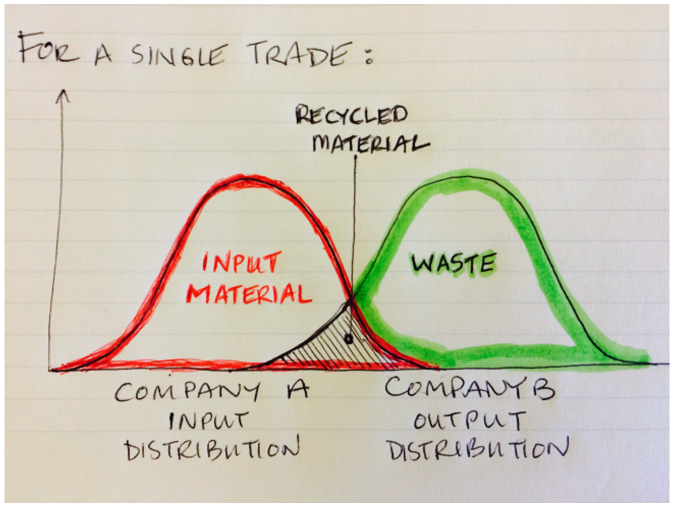

Figure 1. Variables used in calculation of indicators, as determined for one trade between companies (redraw for final paper). Total material input, IM, is the sum of input material for all companies; total recycled materials, RM, is the sum of recycled material for all companies; the total waste, W, is the sum of waste for all companies.

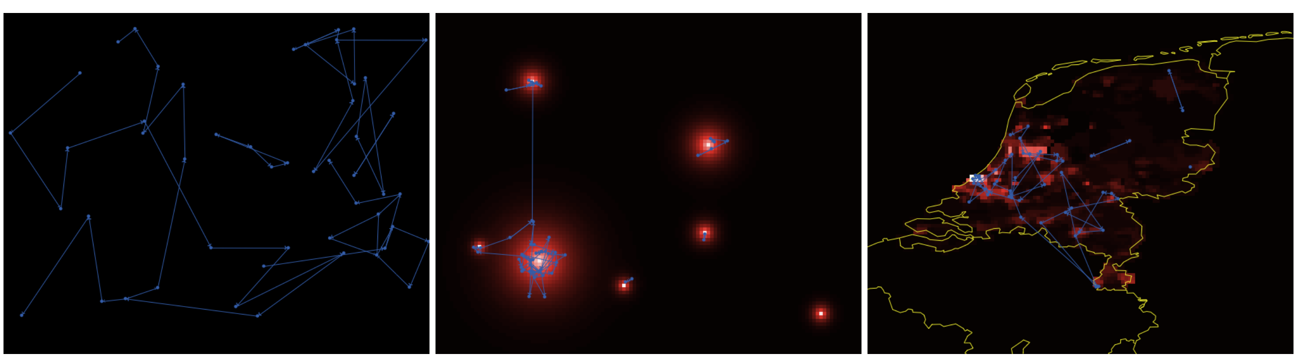

Figure 2. Examples for three possible geographical setups (from left to right, uniform, synthetic city system, real density data)

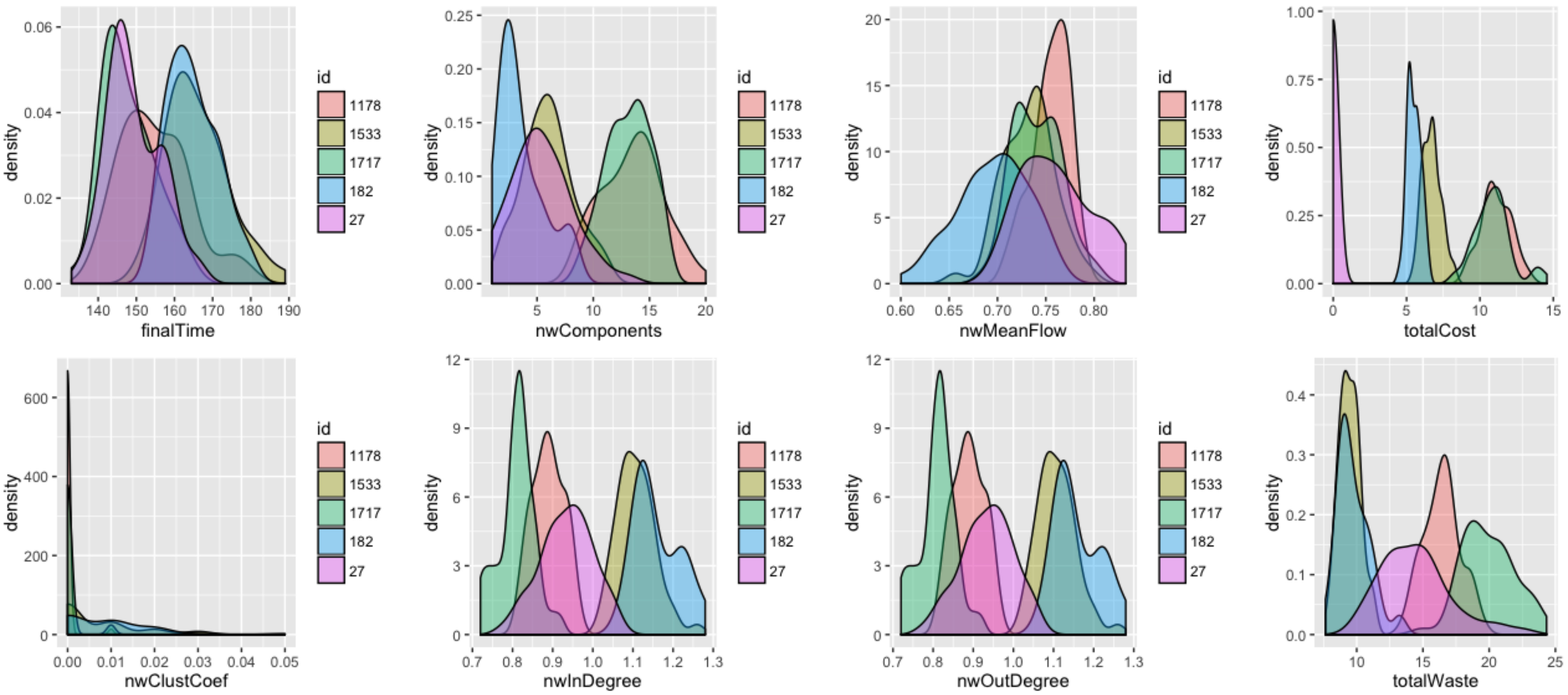

Figure 3. Statistical distribution of indicators for some points in the parameter space.

Results

Implementation

A first prototype was implemented in `NetLogo`. We also developed a `R` version, especially with the objective of an integration into a `shiny` web application for a real world use as described before. Model exploration was done using model exploration software OpenMole[7]. Code and results are available on the open repository of the project[1].

Internal model validation

Statistical Consistency First of all, we verify the internal consistence of the model by looking at statistical distribution of indicators (shown in fig. 3 for some points of the parameter space). Distribution are unimodal but not necessarily normal. We can however roughly estimate the number of runs needed to reach a certain confidence interval on the mean. For example, assuming normal laws, to have a α level CI of width σ around the mean, the result is independent of distributions and verifies $\sigma = \frac{4\sigma \cdot z_{1-\alpha}}{\sqrt{n}}$, what gives $n \simeq 64$. We run experiments with $n = 50$ in the following.

Path-dependency and Emergence

Model Exploration

Uniform spatialization

We ran first experiments with a uniform initial distribution. Figures 5 and 6 show heatmaps and Pareto front.

Synthetic city system

See repository for figures for similar experiments with synthetic system

Real city system

idem

Interesting result : qualitative transition when changing from uniform to real system - implications for decision making ; importance to embed in a real urban system.

[1] at `https://github.com/SFICSSS16-CircularEconomy/CircularEconomy`

Table 1. Regression results for the amount of recycled materials in the system

	Dependent variable:
	Recycled Materials (RM)
Distance decay 1	7.101^{***} (0.164)
Distance decay 1.5	13.045^{***} (0.164)
Distance decay 2	17.503^{***} (0.164)
poly(Length correlation)1	-0.640 (0.985)
poly(Length correlation)2	21.561^{***} (2.312)
Constant	2.846^{***} (0.133)
Observations	2,480
R^2	0.841
Note:	*p<0.1; **p<0.05; ***p<0.01

Spatial correlation input and output distribution

In Table 1 regression results are shown with the amount of recycled materials (RM) in the system as dependent variable for a syntactic city system. The total amount of RM has a minimum of 0 and a maximum of 50 over all simulations. We used two important spatial predictors, all other model parameters are fixed. The first spatial variable distance decay, which is function defining interaction potential between two actors, defined as $exp(-(d_{ij}/\delta))$, where d_{ij} is the Euclidean distance between agent i and agent j and δ is the distance decay parameter. For this example we chose $\delta \in \{0.5, 1, 1.5, 2\}$ The second spatial parameter is the Length correlation between input and output distributions, which is a measure for how well the input and output distributions are matched by geographical location. In the synthetic city system and real population density spatial setup, the distance decay can be interpreted as the probability that companies between 'centers' (cities or industrial parks) interact and the Length correlation is the probability that actors within 'centers' can interact.

As can be seen from Table 1 both predictors together explain 84.1 percent of the variance in this particular setting. Not surprisingly as the Distance decay goes up (and the interaction probability goes up as well), the amount of recycled materials goes up as well. For Length correlation we find a quadratic effect. To get a better overview of what this means the standardized predicted DC scores are plotted in Figure 4 (interactions included). Low Length correlation hardly have any effect on the predicted Degree Circularity of the system, only at high length correlations, 0.4 or higher, does the correlation have effect. These results seem to suggest that matching companies to be located within the same center/city/industrial park only has an effect when the matching is very strict.

Discussion

In this working paper we introduced the basis of an agent based model for modeling industrial symbiotic processes. Industrial symbioses is about 'closing the loop' mechanisms with a clear spatial component. It is therefore interesting to study the effect of these spatial interaction on the functioning of the system as a loop. Our first results indicate that there are clear differences when the model runs on a uniform spatial distribution compared to a synthetic city system or a real world density data. Secondly we found that matching companies in industrial parks only has an effect when the correlation between input materials and waste product is higher than 0.4. This abstract result implies that the design of industrial parks requires some strict central planning to match industrial actors in the same geographical proximity.

Model Extensions

Various possible model extensions for the basic model include for example :

- Bargain games with more than two players, implying game-theory framework to establish links among potential partners
- Random Utility Models

Model extensions for the final paper will be:

- A Google maps integration
- Calibrated to real-world data

The goal for later papers is to make a basis for an open source circular economy application that can be used to monitor the circular economy, as well as create a market place for waste products.

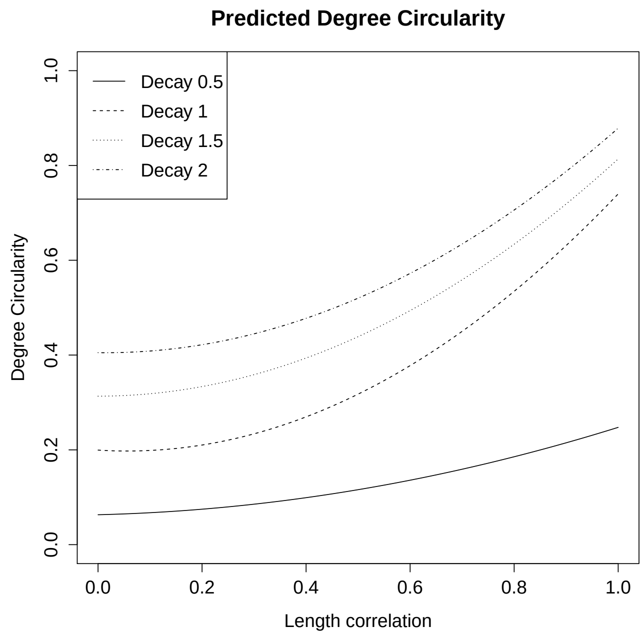

Figure 4. Plot of predicted Degree Circularity

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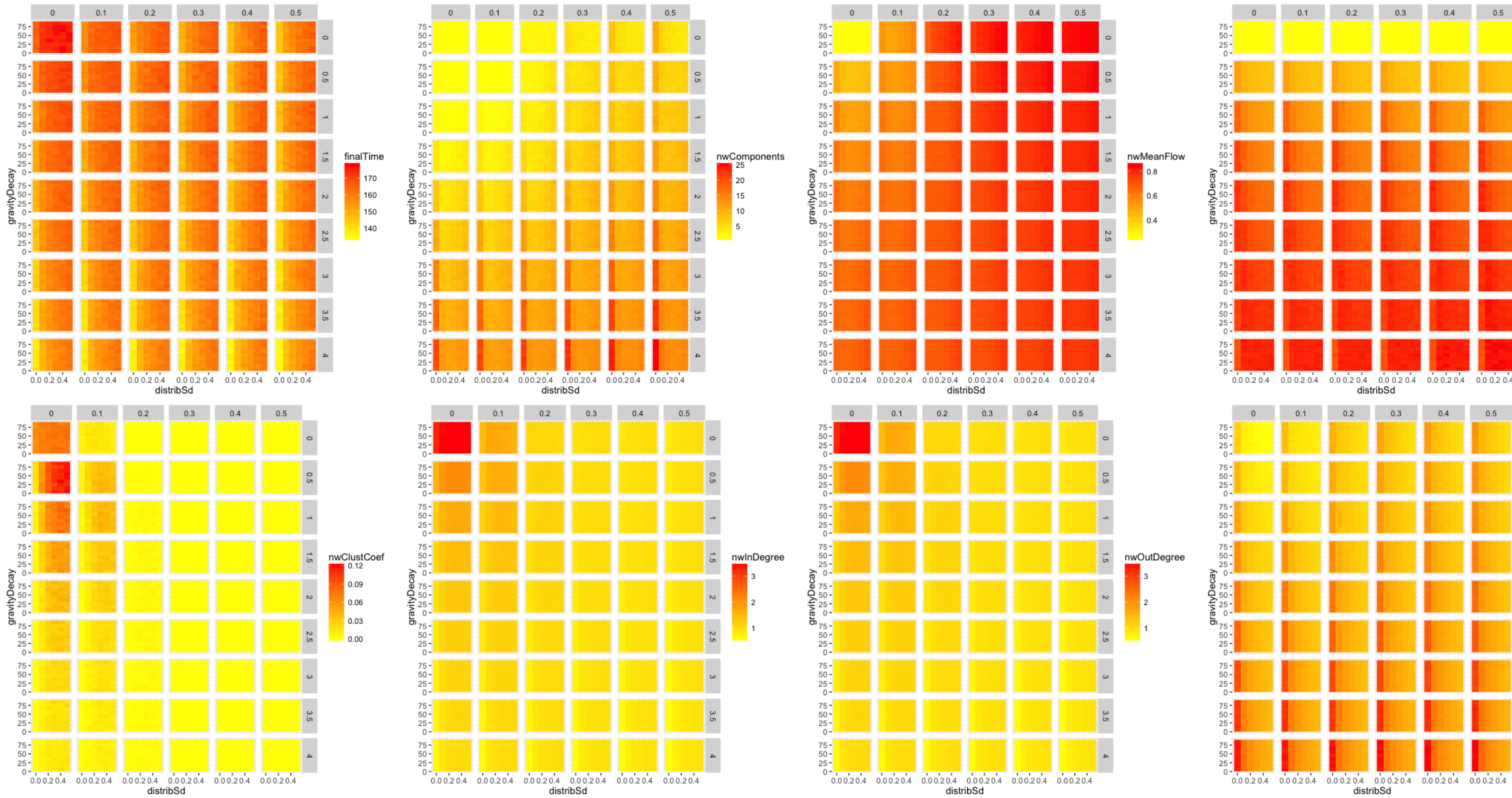

Figure 5. Heatmaps of indicator values in the 4-D parameter space

Supplementary Materials

Model Exploration

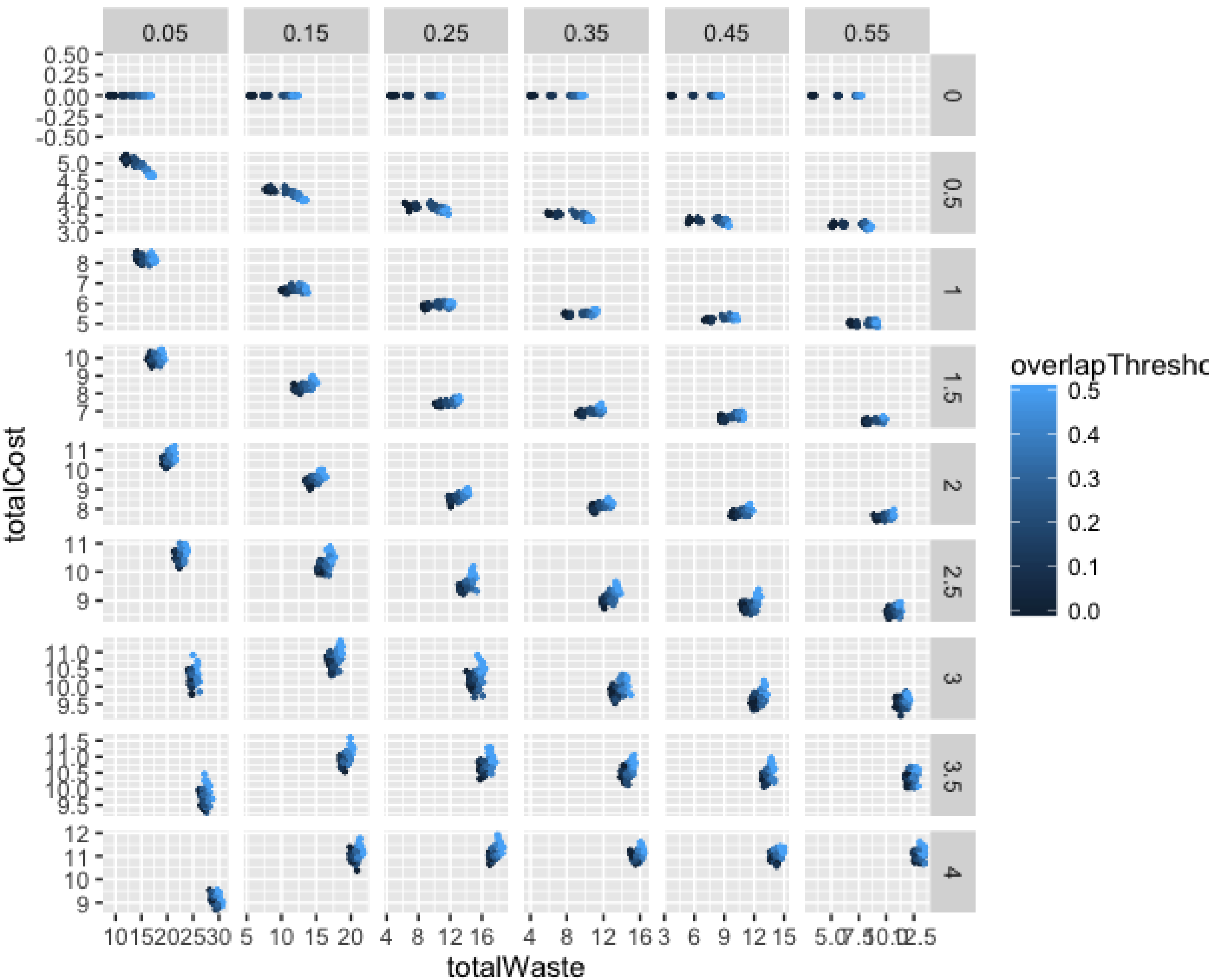

Figure 6. Pareto fronts of total waste against total cost, at fixed values of transportation cost and distribution standard deviation.