# Circular Economy: a Coloured Petri Net based discrete event simulation model

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**ABSTRACT**

Transition from linear economy to circular economy has been so fast due to worsening circumstances stem from climate change and pollution environmental effect. The circular economy has provoked by the emergent need to cope with resources scarcity (e.g. water and food). This economy generates a new way of rethinking and re-design process by re-using the same material, minimise the impact of waste and pollution, and revamp the economy. In this context, cities offer a desirable place for the evolution of the circular economy thanks to their closeness to citizens, companies, and service suppliers. Such cycles, are very interesting systems from a performance evaluation point of view: in this paper we offer an holistic case study by employing Coloured Petri Nets to describe a real case scenario of circular economy. We focus on a very current example which considers the circular production of chitin by bioconversion of municipal waste and we show how we can describe and analyse it by using standard approaches to performance evaluation. The results allow to focus on interesting metrics and performance indicators, which may not be easily obtainable with conventional techniques used in the economic domain.

## I. INTRODUCTION

The global environmental warn is provoking a sense of responsiveness among businesses, governments, no profit organisations and so on. These actors are coping with waste, pollution and resource scarcity, by rethinking, re-designing, and re-using components of existing products. This new process is known as circular economy which is an alternative process to reduce and reuse waste to be converted into a new product. In addition, “recycling what cannot be reused, repairing what is broken, remanufacturing what cannot be repaired” is enclosed in the circular economy process [29]. The life span of each component of a product increases supplying renewable energy. New jobs are offered and new skills are requested, involving the entire ecosystem. [10] point out the fact that the current economy is formed of five helix, that is “university-industry-government, media-based and culture-based public, and environment” which are intertwined in a circular loop of resources and energy for a high level of efficiency [25], [26]. Moving beyond the linear economy which aims to converge natural resources into cheap products driven by the logic of ”take-make-dispose” economic model, the circular economy develops a re-thinking, re-designing, and re-using approach. This approach seeks to adopt a bottom up approach involving citizens for a more sustainable development. Accordingly, urban contexts are becoming more responsiveness than the past to the effect of climate change, over-population, and pollution and so are embracing the circular economy approach. They have a strong experience in offering a “sustainable waste management”? [24]. This also allows a frequent dialogue with territorial actors such as businesses, suppliers, government, citizens, etc. in producing more “durable, reparable and recyclable products”. In addition, the universities are playing a relevant role in training and nurturing new professional skills. These are good initiatives but there still is a concern how those are generated avoiding the deterioration of reused material [7]. Cities so are called to stimulate the pursuance of circularity and achieve sustainability goals thanks to their proximity with all territorial actors. The link between circular economy and cities is becoming popular among scholars [26], [33], [14], [3], [8] but a lack of empirical studies persists [28].

In this paper we present our experience in modelling a case study of Circular Economy using Coloured Petri Nets (CPNs) [17]. The preliminary goal is to provide

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an approach that allows us to analyse the qualitative behaviour of the system under study, i.e., the circular manufacturing of chitin via bioconversion of urban wast. This analysis takes advantage of the benefits of modelling by CPNs [13], [6]. In particular, in this case we were able to quickly define the network representing the real scenario (half an hour). Moreover, the time needed to obtain the results that we show in this work is negligible, that is to say a few seconds. Using other simulation approaches, e.g. ARENA [1] to name one, model development may take days and results can require minutes or even hours to be computed. Other modelling approaches, such as fluid approximations [21], [12] are not suitable since they cannot explicitly consider the combination of entities of different types.
The rest of the paper is organised as follows. In Sec. II, we introduce Circular Economy. Sec. III first provides an example by presenting the role of chitin cycle in urban wast recycling, in line with the case study analysed. Sec. IV first describes the model developed to show the real system analysed and its parameters. Additionally, results are provided leading on metrics and performance indicators. Finally, Sec. V draws some conclusions.

## II. CIRCULAR ECONOMY

Although it is growing popularity, the phenomenon of circular economy started in 1862 by Simmonds who declares the need of generate innovation from the wast which was not efficiently reused. Such need became more pervasive with the rise of environmental issues [27] which induces the shift from a linear economy to a circular economy [2]. This shift is happening gradually. Indeed, nowadays the number of companies which are fully embracing the circular approach is increasing. Living and producing in a circular flow of tangible and intangible resources, the development of the worldwide economy seats on four blocks: 1. re-thinking design model; 2. Circular business model; 3. "recycling and reverse value chain", and 4. Stimulating Eco-innovation. The re- thinking design model (1) employs already used material in a circular loop, enlarging the life span of each single components. It gets closer local, national and global actors aimed at achieving sustainability goals [19]. This stimulates new circular business models (2), that is new architectures developed horizontally enclosed in high territorial proximity. Individuals work in the same environment scaling the reuse of material from a local to a global space. Value chains are based on recycling and reverse (3), where the production starts from the bottom to the up. Citizens are empowering for the reuse of the waste which is delivered the chain of production in order to made a new product. The value creation is not generated linearly but entails a closed- loop system for industries in shich reverse value chain activities (rescue, repair, refurbishing, recycling, remanufacturing, or redesign of returned products from the end user) [31]. Finally, innovations are sustainable and eco-friendly. Referring to the concept of incremental innovation [15], eco-innovations concern the re-use of existing components of a product "rather than the full product" to generate new goods. Metaphorically, the economic system is "cradle to cradle" restoring cycle of nature by the reuse of waste [20] which assumes value for a company [11]. In addition, a bottom up approach is employed which empowers citizens and encourages cities in being more sustainable and facilitators of such change. For instance, in China the government tends to facilitates sustainable businesses mainly at their early stage [32]. In a nutshell, undesirable products become desirable and fruitful for the productivity of natural resources. They are re-used and converted in new selling-goods. Stahel claims reusing waste to offer new services. This takes place on the development of six activities "Regenerate, Share, Optimise, Loop, Virtualise and Exchange" [28] which are employed at a local, national and global level. With a focus on a local level, we draw the attention on cities which are playing a relevant role in the circular economy. They are the new hubs for eco-innovations, striving to improve citizens' life quality [24]. Cities takes up the responsibility of developing smart projects. For example, the smart mobility which aims to minimise the level of pollution. To achieve smart projects, cities can adopt Circular Design Process (CDP), see figure 1. The CDP is formed of four steps referring to the design thinking and the human centred mode: 1. Comprehension of material to explore new re-use; 2. Associating a meaning to material to better define the scope of a designer; 3. Use material to generate new prototypes; 4. Build a narrative storytelling to launch a new material so as to engage customers.

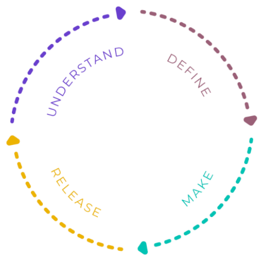


Fig. 1. Circular Design Process.

## III. CASE STUDY: CIRCULAR MANUFACTURING OF CHITIN

In this paper, we selected a circular economy case based on the work presented in [23] where the circular manufacturing of chitin via bioconversion of urban wast is analysed. The problem of global wast is rapidly increasing due to the people trend to move in urban area. Urban citizens generate an amount of wast four times greater than country side residents. For this reason, the management of gathering, storing, and destroying wast is becoming one of the most expensive items for municipalities, both for developing and developed countries. The 2018 global municipal solid wast production was at least 2 billion tons per year and the is estimated to reach 3.4 billion tons by 2050. With this projection the world needs to switch to new models of production and consumption based on sustainable and circular paradigms [30]. [23] specifies that, generally speaking, wast is approximately composed of 60% organic matter from food, vegetables, and garden material; 30% paper, cardboard, textiles, and other cellulosic materials; 12% plastics; 3% metals; and 3% glass, and that for organic streams the main aim is to reduce and valorise. In particular, valorisation of food waste is primarily performed by bioconversion using microorganisms, enzymes, and animals. The extraction of proteins from these entities allows to produce matter for animal or human consumption as well as the production of energy. The example studied in [23] takes into account the black soldier fly (BSF, Hermetia illucens), a popular insect globally for its efficient conversion of a wide variety of organic materials, such as urban and agricultural waste, into biomass. In order to quantify this process it is highlighted that in the average of two weeks required for the instar, the time between egg hatching and the prepupal stage, BSFs process 20 times their own weight in waste. Furthermore, Chitin, constituting 6-9% of BSFs' dry weight, is the second-most abundant organic polymer on earth with annual worldwide bioproduction estimated at 1011 tons across every ecosystems.

Therefore, we opted to model this process since it provides for the first time a general route to embed manufacturing within its surrounding ecosystem. An example of the circular manufacturing of chitinous biocomposites via bioconversion of urban refuse is showed in figure 2.

## IV. MODELLING, SETTINGS, AND RESULTS

In line with the example of circular economy showed in the figure 2, we drawn a new model combining the CPN approach with a real scenario. Petri Nets (PNs) [22] are a modelling tool for the representation of concurrent asynchronous systems. PNs are bipartite graphs where two types of nodes, called places and transitions respectively, are connected by directed arcs. Each place can contain a finite integer number of tokens. The state of the system is given by the distribution of tokens over the places, which is called *marking*. The dynamics of the model is defined by state changes due to firing of transitions, which move tokens over the places. The main advantage is that they provide a graphical representation of complex behavioural such as concurrency, conflict, synchronization, etc. Coloured Petri Nets are an extension that allows the representation of large systems where tokens are augmented with attributes. Attributes are called colours, and are divided in classes called types. Each token has associated a set of types that defines its attributes. A transition is enabled to fire if all the places connected with incoming arrows have enough tokens of the colour associated with the respective arc. When a transition fires, it removes the tokens from its input places and inserts tokens into its output places according to the colours associated with the outgoing arrows. For a tutorial on CPN, the reader can refer to [16].

### A. *THE COLOURED PETRI NET MODEL*

The resulting net is reported in figure 3. We set five different token colours corresponding to the system entities, namely *Products*, *Cellulosic*, *Chitin*, *Insect* and *Protein*. The arcs are labeled only if the transition among the arcs fires tokens of a different color with respect to the one of the incoming arc. For instance, transition *Production* fires a token of color *Product* when 1 token of color *Product*, 1 token of color *Chitin*, and 1 token of color *Cellulosic* are available in place *Plant*, and transition $EndOfLife$ fires 1 token of color *Product* and one token of color *Cellulosic* for each incoming token of color *Product*. Otherwise, transitions firing tokens of the same color of the incoming arc are labelled with the name of the color, e.g., see transition *Biodegradation*.

Our CPN model is implemented with JMT [18]. One interesting feature of CPN is that they are supported by multiple tools [4], [9], [5], we chose JMT for the modern graphical interface. The model shown in figure 4 was developed through some hypothesis and simplifications compared to the original Petri Net of figure 3, which are reported below. For sake of simplicity and in order to focus the analysis on chitin impact, we neglected the protein cycle depicted with greater dashed lines and circles. Furthermore, the chitin path drawn with smaller dashed lines and circles has an immediate transition only, therefore in the implemented CPN it is reduced with only one arc that goes from *Prepupa* place to *Plant* place. The arc in the Production Loop (see figure 2) that goes from Research&Development to the Plant is not reported in the CPN as it represents a conceptual step, but does not involve transfer of entities. However, the product cycle is closed by drawing the arc from the place $End\ Of\ Life\ Products$ to the transition *Recycle* that accounts for product matter directly recycled by the the plant. Finally, we added a source *Food* modelling the food provisioning to the city and a sink[1] place *FoodOut* accounting for the food that comes out of the system.

### B. *MODEL PARAMETERS*

In this scenario, we chose to model each entity required by each stage of the circular production cycle with a single token of the corresponding color: i.e. one token represents the daily amount of a given entity (insects, products, food waste, etc.). All timed transitions $k$ have an exponential firing time distribution and their respective firing rate is indicated with $\lambda_k$. Rate $\lambda_{Food}$, for source *Food*, is set to 1 food token per day. Given that adult BSF lives for 5-8 days and in this time they must find a mate and lay eggs, we set $\lambda_{Eggs}$ equal to 1/4 insect per day accounting for 4

[1] In JMT a Source is used to model entities entering the system and a Sink collects entities leaving the system to allow computation of specific performance metrics.

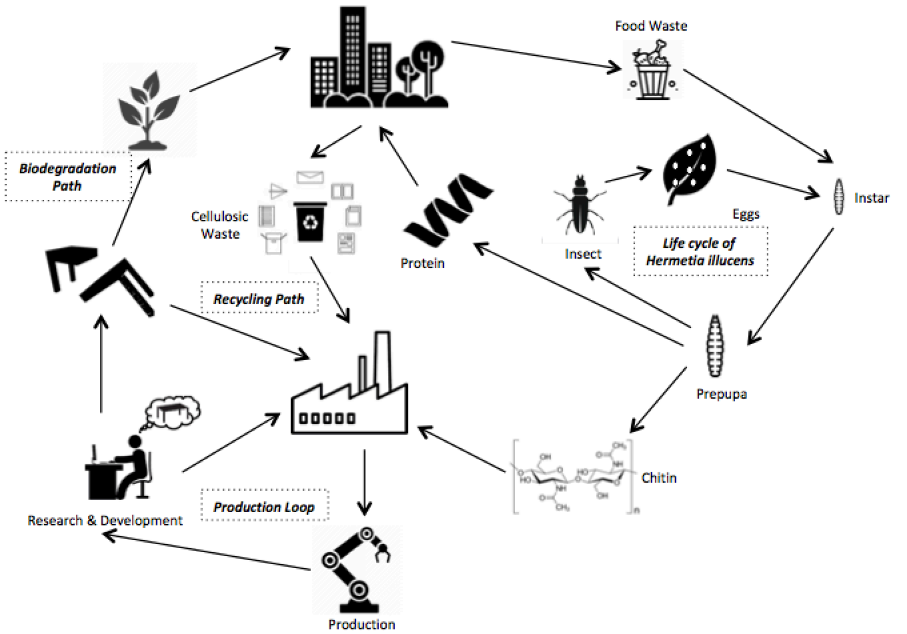


Fig. 2. Chitin cycle in the recycling of municipal waste

days required to hatch the eggs. Then the larvae will take roughly 2 weeks before they are ready to pupate, hence $\lambda_{Prepupa}$ is set to $1/15$ insect per day. Both these transitions are set as infinite server since each insect evolves independently. The initial marking of PLACE *Insect* has been set to 20 to allow the insect evolution process to start. Transitions *Recycle*, *End Of Life*, and *Biodegradation* have their transition rates set to 0.5 per day with infinite server policy. *Food Waste*, *Production*, and *Cellulosic* have their transition rates set to 1.5 per day, and are all single server, i.e., each transition serves one token at a time. These rates have been arbitrarily set since more accurate values require focused studies that are planned for future works. Place *Product* has the initial marking set to 10 to start the production loop.

Another important extension will concern the comparison of results presented in this work with the ones existing in literature derived by different techniques, to assess the strength and limitations of the proposed CPN approach.

### C. *RESULTS*

We have analysed the model with JSimGraph, the discrete event simulation component of JMT, and computed the 99% confidence interval for each metric and index. Since results were characterised by very tight intervals, that would have not been clearly visible in the pictures, we decided not to show them for clarity purposes. We first studied the system behaviour as function of the initial marking of place *Insect* that we denote with $N$. Note that in order to obtain the insect evolution process, given the parameter setting

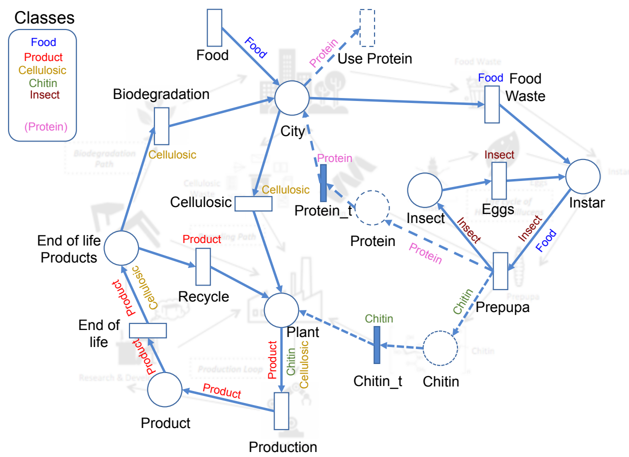


Fig. 3. The CPN based model.

presented above, $N$ has to be greater at least 20 times the daily requirement, since BSF life cycle is set as an average of 19 days where 4 days are for hatching eggs and 15 days are for the instar. We run 7 simulations with $N$ ranging from 10 to 40 tokens with step 5. Indeed, as can be seen in figures 5 and 6 the system is not stable for $N < 20$ resulting in unbounded accumulation of food wast and a simultaneous reduction in production. Figure 6 shows an interesting evolution of food wast in place *Instar* for $20 \leq N \leq 28$ while the system stabilises after $N \geq 30$. We then performed a detailed study of the food waste in place *Instar*, and of the chitin in the *Plant* place, for $20 \leq N \leq 28$, with results shown in figure 7. As expected the accumulated food wast decreases with the number of insects, while

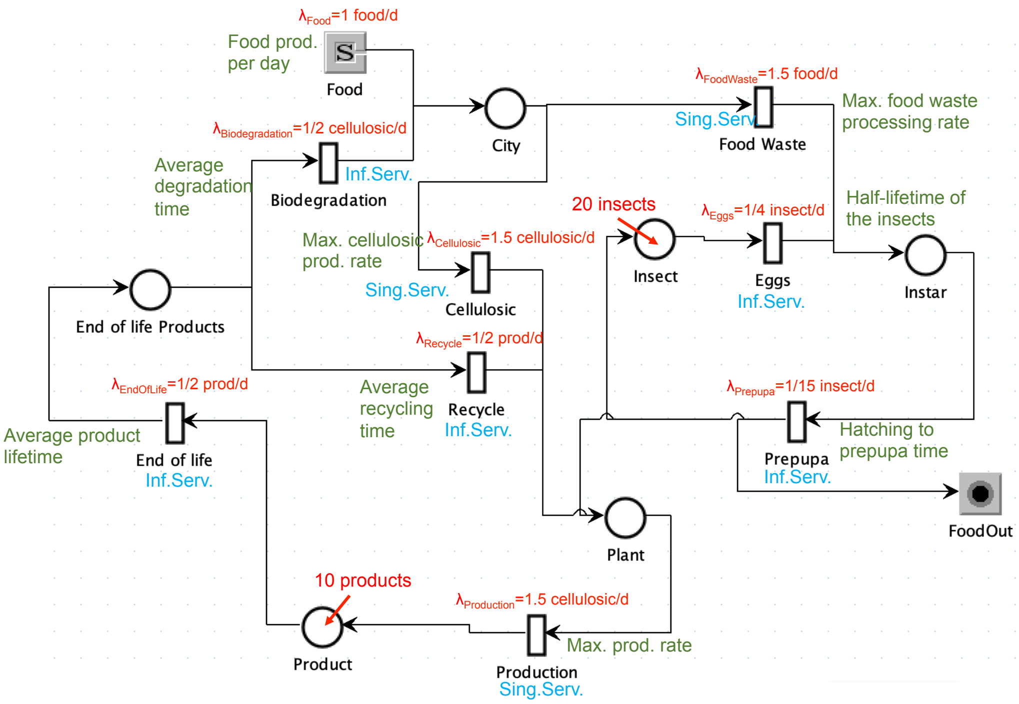


Fig. 4. The resulting CPN implemented on JMT.

the chitin production increases. The figure shows that $N = 25$ gives a good trade-off between chitin production and food waste accumulation.
We further studied the system by setting $N$ to 25 and computed the probability density function (pdf) of the number of tokens in place *Product* (see figure 8), of the number of tokens of class *Chitin* in place *Plant* (see figure 9), of the number of tokens in place *Insect* (see figure 10), and of the number of tokens of class *Instar* in place *Food* (see figure 11). From figures 10 and 11 it is possible to note that the number of *Insects* and *Instar* are distributed with large variability centred around the average time required for hatching and instar. Figure 9 illustrates, as expected, that the Chitin is the most sensitive element of the whole production cycle with a 27% probability of having an empty stock. Figure 8 provides insights about the size of the warehouse to hold products that enter and exit the cycle.

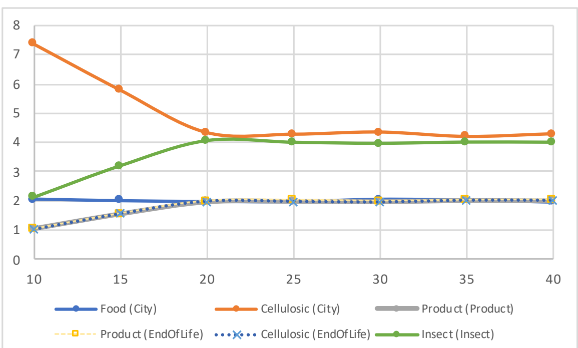


Fig. 5. Average number of *City*, *Product*, *Insect*, *EndOfLife* tokens vs initial marking of *Insect* place.

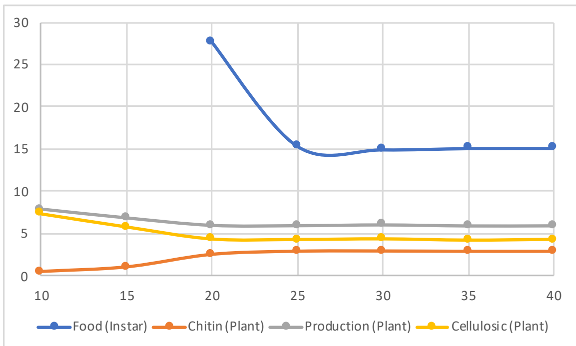


Fig. 6. Average number of *Plant* and *Instar* tokens vs initial marking of *Insect* place..

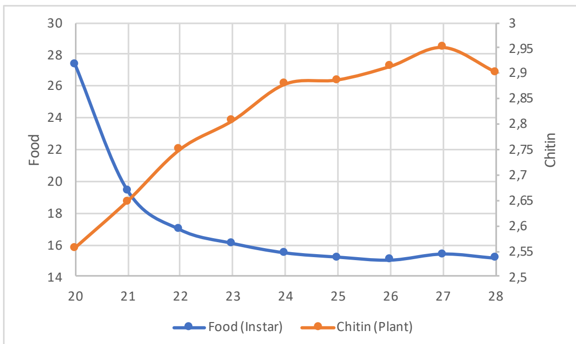


Fig. 7. Average number of tokens of class *Food* for place *Instar* and Chitin for place *Plant*.

## V. CONCLUSIONS

This interdisciplinary work offers a real case scenario of recycling of municipal waste by employing a CPN model. Such model allowed us to get relevant result in a short time. As aforementioned, we were able to get a network of real scenario in half an hour. However, this study has also got some limitations. For instance,

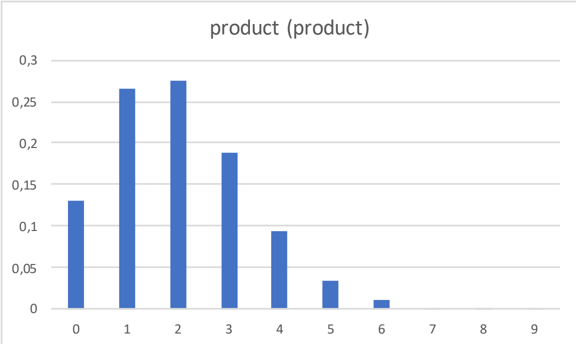


Fig. 8. Distribution of tokens in place *Product*.

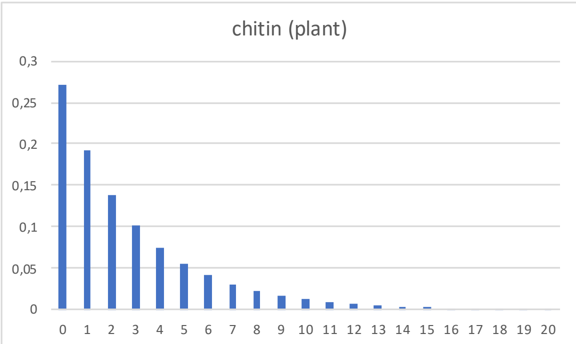


Fig. 9. Distribution of tokens of class *Chitin* for place *Plant*.

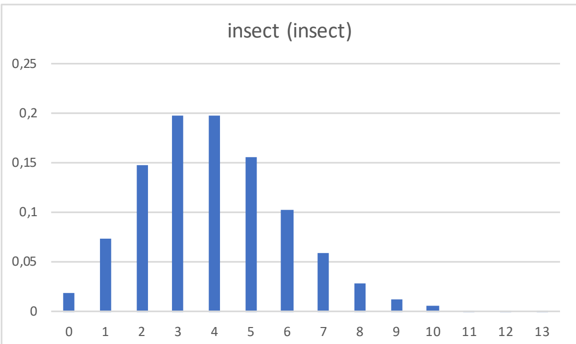


Fig. 10. Distribution of tokens in place *Insect*.

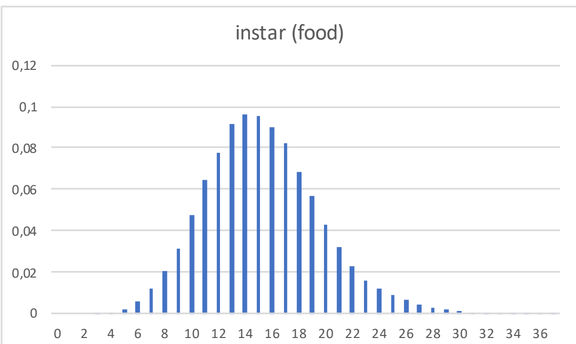


Fig. 11. Distribution of tokens of class *Food* for place *Instar*.

some parameters have been arbitrarily established and part of future developments will aim to focus on a deep investigation to derive a model as close as possible to the real scenario. In addition, this approach will be applied to other case studies to highlight the effectiveness of this technique and to provide relevant ideas for the application of this economic paradigm.

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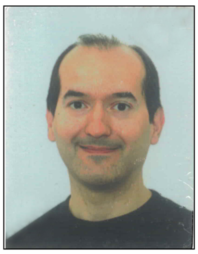

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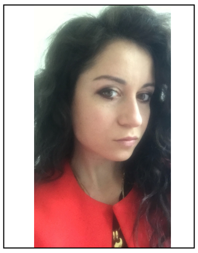

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