# Circular Economy: a Performance Evaluation Perspective

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## ABSTRACT

Circular Economy has emerged in the last years as an industrial pattern that rethinks the entire design and production cycle of products and goods, to obtain the minimal environmental impact and maximize the energy efficiency. This pattern creates product transformation cycles, that allow to re-use parts and renew energy, defining Circular Economy Ecosystems. Such cycles, are very interesting systems from a performance evaluation point of view: in this paper we give a Colored Petri Net perspective to circular economy. In particular, we focus on an example taken from the literature that considers car manufacturing, and we show how we can deal with the problem using standard performance evaluation techniques. Results from performance analysis of the case study, allow to focus on new interesting metrics and performance indicators, that might not be fully studied with conventional techniques applied by expert of the economical domain.

## KEYWORDS

Performance evaluation, Circular economy, Petri Nets

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## 1 INTRODUCTION

There is a world of opportunity to rethink and redesign the way we look for the global competition. Re-Thinking Progress explores how through a change in perspective we can re-design the way our economy works designing products that can be created "to be made again" and powering the system with renewable energy [11]. Among practitioners, policy makers and academics the main question rise up around the consideration whether with creativity and innovation we can build a restorative economy. Looking beyond the current take-make-waste extractive industrial model, a circular economy aims to redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the system. Underpinned by a transition to renewable energy sources, the circular model builds economic, natural, and social capital. The new domain stimulate self-referential and self-tuning economic activities recognising the importance of build and rebuild overall system health through the construction of well-being workspaces at all scales (i.e. large and small businesses, organisations and individuals) globally and locally. Transitioning to a circular economy does not only amount to adjustments aimed at reducing the negative impacts of the linear economy. Rather, it represents a systemic shift that builds long-term resilience, generates business and economic opportunities, and provides environmental and societal benefits.
In this paper we present our experience in modelling a case study of Circular Economy using Coloured Petri Nets [4]. The preliminary goal is to provide an approach that allows to analyse the qualitative behaviour of the system under study, i.e., the end of life vehicles (ELV).

## 2 CIRCULAR ECONOMY

Let us identify four essential building blocks of a circular economy:

1. New Design Thinking: Companies need to build core competencies in a new competition setting based on circular design that facilitate product reuse, recycling and cascading. Circular product and process design requires advanced skills, information sets and new working and knowledge management methods [5]. Areas important for economically successful circular design include: material selection, standardised components, designed-to-last products, design for easy end-of-life sorting, separation or reuse of products and materials, and design-for-manufacturing criteria that take into account possible useful applications of by-products and wastes;
2. New Business Models Architecture: Shifting to a circular economy, it requires innovative and disruptive business models that either replace existing ones or seize new opportunities under new paradigm of scalability as well as replicability

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in reaching significant market share and capabilities along several steps of vertical and horizontal integration between linear value chains. Innovation and digitalization could play a major role in circular economy business models by driving circularity into the mainstream and leveraging their scale up and integration. Whilst many new models, materials, and products will come from entrepreneurs, the major brands and new critical leaders can also play a critical role in order to inspire profitable circular economy initiatives that would be copied and expanded geographically through new business model settings [6].

(3) Recycling and Reverse Value Chain: New and additional skills are requested for cascades and the final return of materials to the soil or back into the industrial production system. This includes delivery chain logistics, sorting, warehousing, risk management, power generation, and even molecular biology and polymer chemistry. With cost-efficient, better-quality collection and treatment systems, and effective segmentation of end-of-life products, the leakage of materials out of the system will decrease, supporting the economics of circular design [10].

(4) Enabling Innovation Conditions: For widespread reuse of materials and higher resource productivity to become commonplace, market arrangement and control mechanisms are dramatically changing playing a dominant role, supported by policy makers, educational institutions and popular opinion leaders. Following the pillars of Quadruple and Quintuple Helix of Innovation [3] Circular Economy emphasizes the role of sustainable and bottom-up gaining from the civil society a new force complementing government, university and industry policies and practices. The quintuple helix views the natural environments of society and the economy as drivers for knowledge production and innovation that it incorporates the circulation of knowledge. The antecedents of this framework are: Open Collaboration, New International environmental rules, Technology for driving fast scale up, and Crowdsourcing and participative financing. Focusing on connections between operators, stakeholders and industrial ecosystems, Circular Economy aims at creating closed-loop processes in which waste serves as an input, thus eliminating the notion of an undesirable by-product, and designing production processes in accordance with local ecological constraints whilst looking at their global impact from the outset, and attempting to shape them so they perform as close to living systems as possible social and urban wellbeing contexts.

As well, we can identify 4 principles underpin Circular Economy Ecosystems:

1. Radically increase the productivity of natural resources: through radical changes to design, production and technology, natural resources can be made to last much longer than they currently do. The resulting savings in cost, capital investment and time will help to implement the other principles.
2. Shift to biologically inspired production models and materials in order to eliminate the concept of waste by modelling closed-loop production systems on nature's designs where every output is either returned harmlessly to the ecosystem as a nutrient, or becomes an input for another manufacturing process.
3. Move to a service business model, providing value as a continuous flow of services rather than the traditional sale-of-goods model aligns the interests of providers and customers in a way that rewards resource productivity.
4. Reinvest in natural capital - As human needs expand and pressures on natural capital mount, the need to restore and regenerate natural resources increases.

Since the Forth industrial revolution, the rapid escalation of technology and innovation mean that many now have access to products from all over the world at affordable prices. The new normal for competition become when the product is, how it is manufactured, how it is used and what happens when it is no longer needed or wanted. It is exceedingly difficult to patronize a new way to design, make, and use things within planetary boundaries, shifting a system that involves everyone and everything. City life play a central role in the global economy representing nowadays creative, responsible and sustainable hubs for innovation [1]. The application of circular economy principles to urban development will create cities that are able to thrive in the long-term, bringing prosperity to their citizens within planetary boundaries [7]. With high concentration of resources, capital, data, and talent spread around small geographic area, cities are uniquely positioned to drive a global transition towards a circular economy. As matter of fact, buildings, mobility, products and services, and food systems as urban systems play an important role in our lives and can have significant impact on social well-being taking care of new opportunities offered by innovations in design, business models and digital technology [9].

There is no single way to design, Circular Economy is an iterative process that should constantly be testing and refining how your users interact with the product and how it fits within the wider system. The evolution of design approach does not dictate holistic metrics and methods, rather identify certain comparable strategies that appear to be more regularly successful than others.

In figure 1, we can fit a Circular Design Process (CDP) that settle four stages based on design thinking and human-centred design:(i) Understand means to get to know the user and the system,(ii) Define means to put into words the design challenge and your intention as the designer, (iii) Make means to Ideate, design, and prototype as many iterations and versions as you can, (iv) Release means to launch your design into the wild and build your narrative - create loyalty in customers and deepen investment from stakeholders by telling a compelling story.

Compared to the traditional design approaches that place a particular focus on considering and meeting the needs of the end user, the design for the circular economy need considering not only the user but the system within which the design will exist. This means understanding the impact of our design on stakeholders and building in feedback loops to help identify and address the unintended consequences of our design decisions. At every stage of the design process, the decision makers oscillate continuously between these two equally critical perspectives: users' need and technology readiness [8].

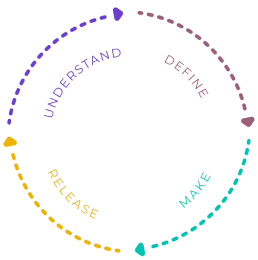

**Figure 1: Circular Design Process.**

## 3 CASE STUDY: END OF LIFE VEHICLES

The automotive sector also benefits from a well - guided flow relating to the end life of vehicles (ELV). In fact, until the year 2000 a specific European directive (2000/53) included one set of rules to ensure that end-of-life vehicles are managed across Europe guaranteed environmental standards. In summary, the directive is based on the principle of extended manufacturer responsibility car that must:

(1) designing new 95% recyclable and recoverable vehicles (homologation constraint);
(2) avoid the use of heavy metals (Pb, Cd, Hg, Cr) with some exceptions (annex 2 directive) in continuous evaluation and elimination;
(3) to guarantee the customer a network of self-demolition centers that collect the vehicles to be demolished at no cost (except for cancellation fees and any transport);
(4) support the supply chain to achieve the reuse and recycling target of 85% by weight and reuse e recovery of 95% by weight.

The vehicle chain is life structured in a similar way throughout Europe, in the following it is illustrated the Italian supply chain formed by:

- about 1500 car wreckers who receive vehicles from end customers or dealers, carry out the remediation, safety, dismantling of components for reuse, dismantling of materials for recycling;
- about 350 scrap dealers or scrap dealers who carry out the volumetric reduction activity end-of-life vehicles and optimize logistics;
- about 20 large crushers that receive the parcels, crush and separate the ferrous and non-ferrous metals and fluff and deliver the materials to steel mills and metal foundries.

Figure 2 illustrates the supply chain in Italy.

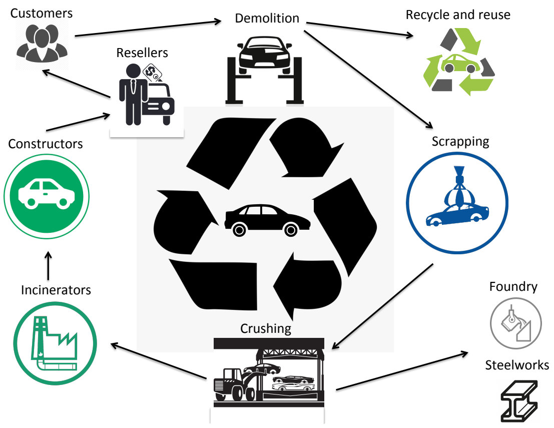

**Figure 2: Circular Economy, a case study: the end life vehicles flow.**

## 4 THE COLOURED PETRI NETS MODEL

Given the end of life vehicles case of Circular Economy presented in the previous section (see figure 2), we derived the workflow depicted in figure 3 to subsequently represent this system through the CPN shown in Figure 4. The different phases of the process are represented with boxes: Dem(olition), Recycle, Scrap(ping), Crus(hing), Steel(works), Foundry, Inc(inerators), Cons(tructors), Resellers, and Customers. Blue boxes are used for the main cycle, while orange boxes denote phases of secondary cycles. To simplify the description, we identified four different entities forming the system: cars, parts, steel, and energy. Their dynamics are represented with different colored arrows. In particular, red arrows denote resources entering the system, green arrows denote entities abandoning the cycle, while blue arrows denote transfers between the phases. The yellow line splitting the reseller in two, denotes that such entity is usually crossed two times in the cycle: at the beginning, where owner returns their used cars, and at the end, when new cars are sold.

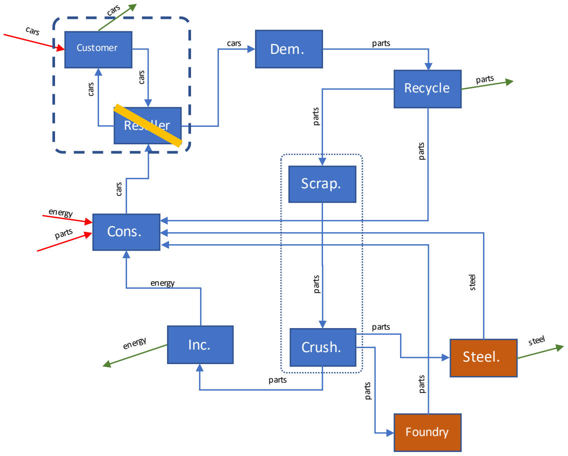

**Figure 3: Workflow of the considered scenario.**

The resulting CPN model implemented with JMT [2] is reported in figure 4. We set four different token colors corresponding to the above mentioned system entities, namely *Cars*, *Parts*, *Steel*, and *Energy*. In-flows (red arrows in figure 3) are modelled with sources[1], and out-flows (green arrows) with a timed transition connected to a sinks[2]. Petri net places model the buffers of the considered stages:

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[1] JMT does not support timed transitions that are always enabled: entrance in the system is modeled with special primitives that are source nodes.
[2] Sinks collects entities leaving the system to allow computation of specific performance metrics.

to simplify the presentation, customer and resellers have not been modelled (box dashed line in figure 3), and the "Scrap" and "Crush" box have been merged in a single place (box with dotted lines) since they simply process the input and communicate through exactly one request. Blue arrow flows in figure 3 are transformed into conventional timed transitions that connect places modelling the interconnected phases.

The notations of figure 4 are explained below. All timed transition have an exponential firing time distribution and their respective firing rate is indicated with $\lambda$. Rate $\lambda$ is used also for sources (i.e. *UsedCars* and *ExternalResources*). The arcs are labeled only if they have a weight greater than 1 and/or if the transition among the arcs fires tokens of a different color with respect to one of the incoming arc. For instance, transition *Dem_T* fires 10 tokens of color *Parts* for each incoming token of color *Cars*, transition *NewCar* fires a token of color *Cars* when 4 tokens of color *Parts* and 1 token of both colors *Steel* and *Energy* are available, and transition *SoldSteel* fires 1 token of color *Steel* for each incoming token of color *Parts*. Arcs with no label are meant with weight equal to 1. Places that are bounded are labeled with their respective maximum capacity $C$: if such limit is reached, new tokens arriving are simply discarded. We have analyzed the model with JSimGraph, the discrete event simulation component of JMT, and computed the 99% confidence interval. Figure 5 shows the production rate of the various markets, computed as the throughput of the corresponding sink nodes. As it can be seen, in this circular economy example, parts generate the highest volume, while cars represents only a more limited contribution. The figure shows also that the model has a minimal global drop rate: the total number of cars, parts, energy or steel that has to be discarded due to overflow in any part of the system.

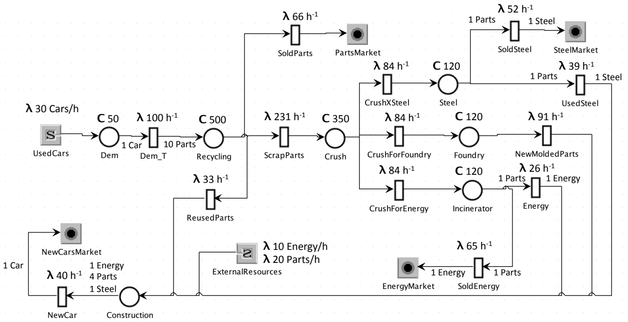

**Figure 4: CPN model. Firing or arrival rates are prefixed with $\lambda$, place capacities with $C$, and colors and quantities of tokens required or produced by a transition are denoted with labels assigned to their input and output arcs.**

Figure 6 shows the distribution of tokens in place *Construction*, that represents the availability of resources to produce new cars. As it can be seen, buffers have almost a bi-modal distribution: a peak with warehouse almost empty, plus an almost uniform distribution for all the possible occupations. This information can be helpful in correctly sizing the infrastructure to support a circular economy process.

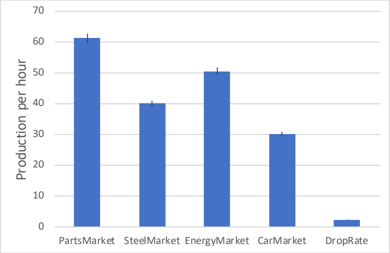

**Figure 5: Production rates of the considered markets.**

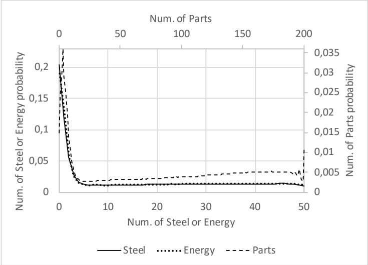

**Figure 6: Distribution of tokens in place *Construction*.**

## 5 CONCLUSIONS

This short paper has been a preliminary interdisciplinary work to test the opportunity of using performance modelling as a tool for circular design and for supporting circular economy. Although results are still at an early stage, the opportunities seem to be promising, and they deserve to be more deeply investigated in future works.

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