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De-Production model combining R-Strategies and D-Strategies in product and production systems life cycles: Application to Remanufacturing

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Abstract

The world faces unprecedented challenges related to the so-called Triple Planetary Crisis (climate changes, massive pollution, biodiversity losses). The Linear Economy model of development represents a very relevant cause for these crises effects, since it is anchored on the paradox of ever-growing natural resources extraction within a finite planet space and limited policy barriers for ecosystems degradation. Circular Economy emerges as a promising alternative development model, but it still urges for effective implementation. This work presents a novel De-Production model that combines, by design or redesign, the articulation of R-Strategies and D-Strategies across the product and production life cycles in order to unblock circular business models. It is proposed a systemic approach considering product circularity by means of activating R-Strategies, improving both production operations and de-production operations via value retention mindset. The model is tested via discrete simulation in a remanufacturing case study of a bicycle wheel assembly.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction and state-of-the-art

The planet is currently facing a decisive moment in terms of its ability to take actions capable of mitigating the effects of pollution and climate change. On the one hand, there is the massive volume of greenhouse gas emissions into the atmosphere, on the other hand, the economic development model supported by the highly optimized Linear Economy model of – Extract > Produce > Use > Discard – has given rise to an enormous and still growing need for the extraction and consumption of material resources. As a consequence, the world ecosystems suffer of accelerated deterioration due to over consumption and overproduction [1] and current environmental footprint of humankind is not sustainable within Earth's finite natural resources [2]. Material use and waste levels are expected to increase more in the coming years, as the global population and human demands on the planet's resources are on the rise [3]. As a countermeasure to these risks and challenges related to climate change, Circular Economy (CE) has gained momentum in the political agenda as a promising economic paradigm enabling governments, enterprises and institutions to reduce their environmental impacts, resource use and waste generation [4]. The vision of the Circular Economy paradigm is to fundamentally change the current linear "take–make–

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dispose" economic approach, which is cause of massive waste flows It is therefore imperative to find ways to resolve the obstacles that continue to exist in the implementation of business models supported by the Circular Economy. [5].

Over the course of a century, namely after the work of Frederic Taylor on scientific management on industrial operations, production systems and value chains have undergone a significant leap in productivity, optimizing cost reduction, processing times, product quality, etc. Industrial sectors and societies have crossed different technological driven industrial revolutions (Industry 1.0, 2.0, 3.0, and nowadays 4.0 and emergent 5.0). Along each revolution, a continuous concern for manufacturing firms is the mismatch between supply and demand within value chains [6], but cross-linking improved organization methodologies and management practices (e.g. Toyota Production System), globalized supply chains, and with all kind of technology advances (manufacturing, computational, information systems) allowed vast amount of productivity gains to fulfill demand. It can be inferred that modern production systems have been a fundamental instrumental, to companies' economic grow strategies, and "an invisible ally" for consumers wishes and growing demands, that reinforced the prevalence and optimization of the Linear Economy Model.

Despite the myriad aspects and topics encompassing the designated R-Strategies or R-Imperatives, such the systematized and focused 9R approach [7] (Kirchherr et al., 2017) [8], multiple challenges remain in a fast pace circular business models implementation. More than 55 R strategies can be directly involved within CE frameworks and waste management, and more than 100 R in a broader sense that deals with circularity towards a low-carbon society [9]. Different types of blockers and difficulties persist, in different sectors to effective implementation of CE in the use phase, such as the packaging sector, electrical and electronics sector, durability of products, need for different players, the importance of top management, CE level approach, renting as a business model, remanufacturing and reprocessing of electronic equipment and engines, options to sell products in bulk and raising people's awareness of the importance of CE throughout the product's life cycle [10]. Other typical challenges on CE relate to the need of product reconfigurability capabilities that enhance sustainable end-of-life management, and that sustainable product design is a mechanism through which sensing and seizing capabilities promote sustainable end-of-life management [11].

In the work of [12] a systematic review drill on the main obstacles that prevent CE from being a reality and the possible actions to overcome them. The analysis found a wide discussion on key CE aspects as, de-manufacturing, disassembly and re-manufacturing [12]. De-manufacturing is a wide concept where "De- or D-" operational strategies typical related as instrumental technical approaches (e.g. disassembly, dismantling, detach, etc.) or sometimes in a higher level concept as proposed by [5] where an aeronautic use case is given focusing "D1- decommissioning", "D2-disassembly", and "D3-smart dismantling". Observing the current literature gaps and organizational challenges that companies and nations face towards more effective circularity, that can mitigate greenhouse gas emissions related to raw-materials massive extraction and waste streams, this paper presents two main contributions. Firstly, an initial proposal for the structure of D-Strategies as operational instruments to unblock technical challenges in R-Strategies behind Circular Business Models. Secondly, a De-Production Model relating the R-Strategies and Product and Production Life Cycles. A proof of concept example is provided by means of discrete event simulation model of a bicycle product, where a wheel module is analysed in two end of use-phase scenarios (very good and medium functionality level conditions).

2. The role of D-Strategies on Circular Economy and De-Production Concept

Circular Business Models can be materialized, depending on the nature of the product and service, by an adequate design that fits in the R-Strategies, where low-numbered R- represent higher circularity levels in terms of material use and/or energy demand, in the common 9R Framework [7] [8]. Fig. 1 presents a proposal for D-Strategies operational strategic roles related to 9R Business Strategies implementation and Circular Business Models.

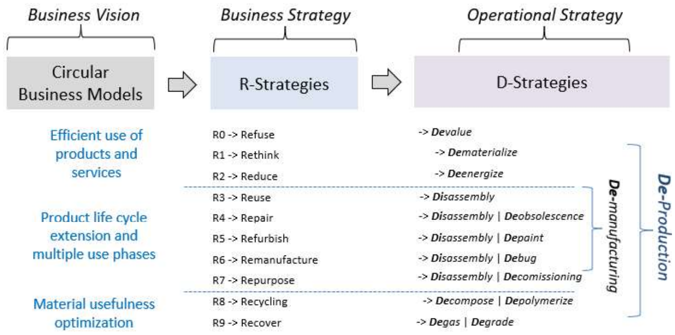

Fig. 1. D-Strategies operational roles examples related with 9R Circular Economy framework and Circular Business Models.

The diagram presents D-Strategies examples, in a systematic form, taking into consideration the importance ladder of circularity implicit on 9R and within the context of products (mechanical and mechatronic based). The exercise focus the relation of each D- with the affinity level R- with literature examples and the author's own opinion. R0-Refuse can be related to product Devalue, meaning that products and objects lose their meaning and, therefore, importance for the consumer [13]. R1-Rethink and R2-Reduce share the advantages of Dematerialization, where, for instance, material can be reduced by shared platforms for products and services, and use of digitalization that obviates material resources [14] [15]. Deenergize refers, in this context, to the product design efforts to reduce energy consumption [16] or even to eliminate the need to use external energy, e.g., use gravity potential energy or passive forms with coils for instance with Karakuri Kaizen design [17]. The group of Rs related to product life cycle extension and multiple use phases where different R-Strategies such R3-Reuse, R4-Repair, R5-Refurbish, R6-Remanufacturing and even R7-Repurpose, all demand for product Disassembly or Dismantle (depending the sector or terminology) [18] [19] [20] [21] [22]. The group of Rs from R3-R6 can be considered directly linked to De-Manufacturing strategies, encompassing also as an enabler to R7-Repurpose. In this latter, a very important D-Strategy consists in Decommissioning complex products, systems or large machinery [23] [24]. For R8-Recycling, two well-known Ds can be related, Decompose for material components [25] and Depolimerize for the specific case of polymer materials [26]. Finally, in R9-Recover, techniques of making use of recover materials such as Degas (Degasification) for instance in lignocellulosic materials [27] and Degrade (Degradation) of materials [28].

When analysing the life cycle of both product and related production systems, the concept of De-Production must be considered as an integrated approach for tackle with more effective and efficient Circular Business Models and the nowadays new directives and regulations towards Extended Producer Responsibility [29]. De-Production Systems and associated life cycle stages, is intended as englobing the De-Manufacturing strategy, so, as a broader scope and for multi-sectorial industries. A given De-Production facility must deal with different R-Strategies, acting as provider of components, modules, and intermentioned products, either for product life cycle support for product extension until End-of-Life (EOL), to feed the in-production new product (Production Factory, blue arrow in the Fig. 2 diagram), or with Repaired, Refurbished, or Remanufactured products. Thus, the De-Production Factory acts as a receptor entity in the context of Industrial Symbiosis, receiving products in the end of a given use-phase or End-of-life. The sub D-Strategies are activated as internal instruments and processes of the De-Production Factory of facility.

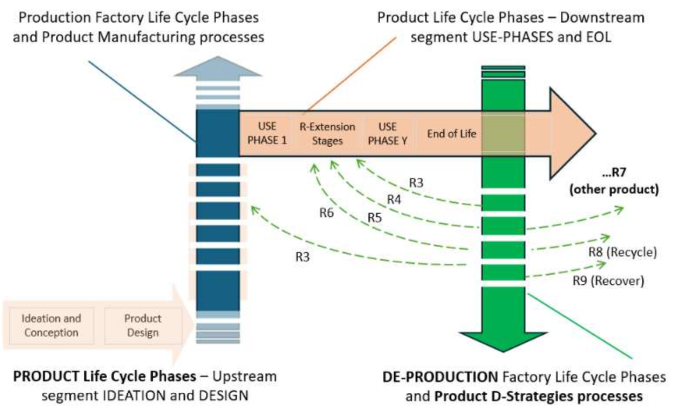

Fig. 2. D-Strategies operational roles examples related with 9R Circular Economy framework and Circular Business Models.

3. Proof-of-concept using a discrete simulation model

This section presents a preliminary case study of a bicycle wheel De-Production system in the context of De- and Remanufacturing. The goal is to showcase the potential of using tools such as discrete event simulation to deal with the complexity (mainly uncertainty regarding the condition of each product or module and variability in performing activities or tasks) and retrieve relevant information to support decision-making for further process improvement.

3.1. Product composition and process description

Regarding the product, the case focuses on an after-use phase bicycle front wheel containing components and sub-modules, namely: valve cap, valve fixing nut, quick release axle, and the wheel module, which includes the tire, inner tube, and rim module. The rim module comprises the rim, spoke nipples, spokes, and hub. The entire wheel enters the system already decoupled from the bicycle and follows an iterative set of inspection-disassembly processes, considering precedencies. The instance created for analysis follows the following sequence of process steps:

1. **Reception** (Initial Wheel): The process begins with the reception of bicycle wheels at a rate of 2 wheels per hour. This sets the stage for the entire De-Production workflow, ensuring a consistent flow of materials for processing.
2. **Initial Assessment**: Each received wheel undergoes a general quality check. Approximately 5% of the wheels are rejected due to severe defects and are moved directly to recycling, ensuring that only processable wheels move forward.
3. **Disassembly Phase 1**: The wheel is disassembled into major components: the valve cap, valve fixing nut, quick release axle, and the wheel module. This phase breaks down the wheel into primary parts for further inspection.
4. **Inspection and Decision Point** (Phase 1 Components): Each component from the initial disassembly is inspected to assess its quality. Depending on the inspection results, components are routed to the next processing phase, directed toward the most appropriate R-strategy (Reuse, Repair, Refurbish, Remanufacture, Recycle).
5. **Disassembly Phase 2**: The wheel module is broken down further into sub-components: the tire, inner tube, and rim module. This phase refines the disassembly, allowing more detailed inspections.
6. **Inspection and Decision Point** (Phase 2 Components): The sub-components from the wheel module are inspected for quality. They are then assigned to the appropriate R-strategy based on their condition and usability.
7. **Disassembly Phase 3**: The rim module is disassembled into its smallest components: rim, spoke nipples, spokes, and hub. This phase completes the breakdown of the wheel, enabling comprehensive quality assessments.
8. **Inspection and Decision Point** (Phase 3 Components): The final components (rim, spoke nipples, spokes, hub) undergo inspection to determine their condition. Each component is directed to the appropriate R-strategy: repair, refurbishment, remanufacturing, or recycling.
9. **Processing Stations**: Components are processed at various stations based on their assessed condition:
   - **Repair** Station: For minor repairs to restore parts to working condition.

- **Refurbishment** Station: For parts needing more extensive work.
- **Remanufacturing** Station: For components requiring complete rework.
- **Recycling** Station: For parts beyond reuse, repair, or refurbishment.

For each process above identified, only a workstation cell per process was considered, meaning there is limited capacity to perform the entire process.

3.2. Simulation model and relevant data

After process mapping, the instance was modelled in a simulation model using version 24 of Flexsim software. The simulation model uses a mixed approach between discrete-event and agent-based simulation (through the Process Flow and several Object Process Flow, respectively), to dynamically illustrate the case study and correspondent logistics system in the 3D model. In terms of data, following the fixed rate of arrival, it also considers different statistical distributions in terms of task duration. In particular, for inspection and disassembly, Table 1 presents the correspondence between the sub-module/component and the probability function to reflect real-world variability.

Table 1. Statistical distribution for inspection and disassembly tasks duration in seconds for each component/module.

Component / Module	Average Inspection Time (s)	Average Disassembly Time (s)
Complete Wheel	Triangular (120, 180, 300)	Normal (300, 60)
Valve Cap	Uniform (20, 60)	Triangular (30, 60, 90)
Valve Fixing Nut	Uniform (20, 60)	Triangular (30, 60, 90)
Quick Release Axle	Normal (120, 30)	Triangular (120, 180, 240)
Wheel Module	Normal (240, 60)	Normal (360, 90)
Tire	Triangular (90, 120, 180)	Triangular (180, 240, 300)
Inner Tube	Normal (120, 30)	Triangular (120, 180, 240)
Rim Module	Triangular (240, 300, 360)	Normal (420, 60)
Spoke Nipples	Uniform (30, 90)	Triangular (60, 120, 180)
Spokes	Normal (180, 30)	Normal (300, 60)
Rim	Triangular (180, 240, 300)	Normal (360, 90)
Hub	Normal (180, 30)	Triangular (180, 240, 300)

3.3. Simulation scenarios and results assessment

After modelling the process, two scenarios were defined to assess the impact of different product conditions on R-strategies activation and consequent impact on the Key Performance Indicators (KPIs). Table 2 shows the probabilities for each R-strategy for components in good condition (Scenario 1) and medium/bad condition (Scenario 2).

Table 2. Scenarios definition - the probability of activating an R-strategy for each component/module.

Component / Module	Scenario	R3	R4	R5	R6	R8
Complete Wheel	1	60%	20%	15%	3%	2%
	2	25%	20%	30%	10%	15%
Valve Cap	1	55%	20%	15%	5%	5%
	2	15%	25%	30%	10%	20%
Valve Fixing Nut	1	50%	25%	15%	5%	5%
	2	20%	25%	30%	10%	15%
Quick Release Axle	1	70%	15%	10%	3%	2%
	2	30%	20%	30%	10%	10%
Wheel Module	1	40%	30%	20%	5%	5%
	2	15%	25%	30%	10%	20%
Tire	1	50%	25%	15%	5%	5%
	2	25%	20%	30%	10%	15%
Inner Tube	1	65%	15%	15%	3%	2%
	2	30%	20%	25%	10%	15%
Rim Module	1	55%	20%	15%	5%	5%
	2	20%	25%	30%	10%	15%
Spoke Nipples	1	60%	20%	15%	3%	2%
	2	25%	20%	30%	10%	15%
Spokes	1	65%	15%	15%	3%	2%
	2	30%	20%	25%	10%	15%
Rim	1	70%	10%	15%	3%	2%
	2	35%	15%	25%	10%	15%
Hub	1	60%	20%	15%	3%	2%
	2	25%	20%	30%	10%	15%

Considering the stochastic characteristics of the case instance, 20 replications per scenario were conducted in the Flexsim's Experimenter tool to obtain precise and comparable results. The chosen simulation period was 1 week, considering 7 days of consecutive time (without stoppages – always available).

Fig. 3 presents the simulation results for the type of intervention: Repaired; Reused; Refurbished; Recycled; Remanufactured; Total Processed.

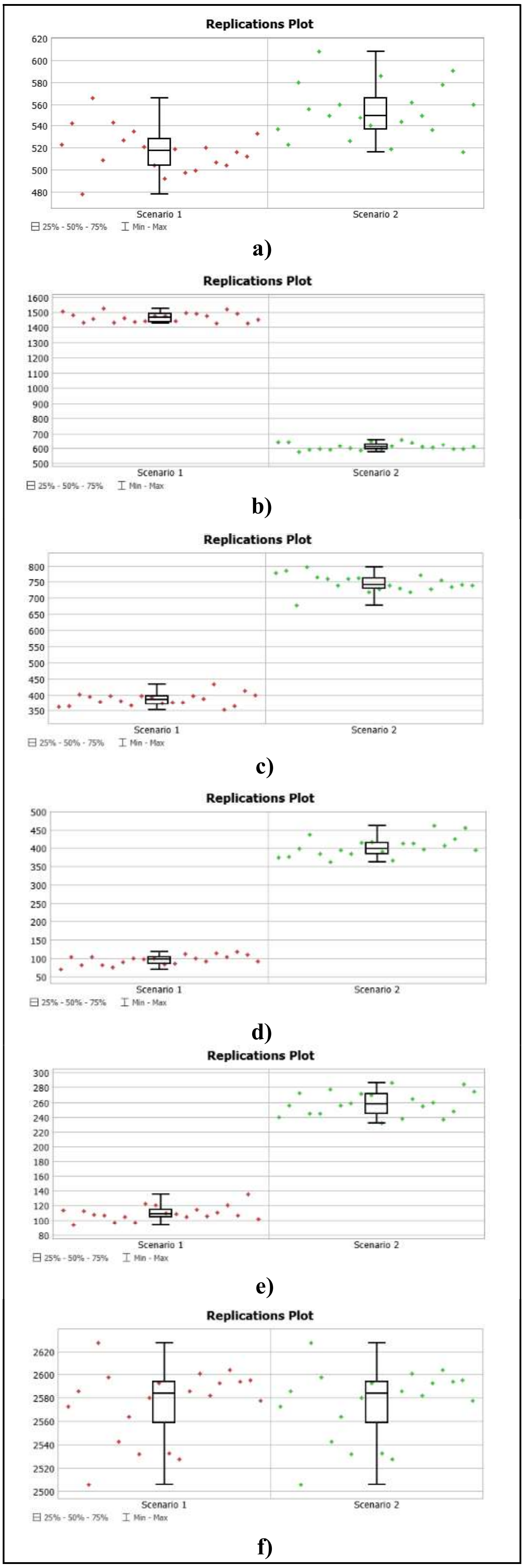

Fig. 3. (a) Total Repaired ; (b) Total Reused ; (c) Total Refurbished; (d) Total Recycled ; (e) Total Remanufactured ; (f) Total Processed.

The simulation results revealed significant differences between the two scenarios. Scenario 1, representing wheels in good condition, showed a higher percentage of parts processed under higher-value R-strategies, such as reuse (R3) and repair (R4). Conversely, Scenario 2, involving wheels in medium/bad condition, showed a greater distribution towards lower-value R-strategies like refurbishment (R5) and recycling (R8). The total parts processed under each R-strategy indicated that good quality components tend to be directed more towards reuse and repair, highlighting the efficiency benefits of initial quality. The continuous operation over a simulated week with 20 replications ensured that the variability was accounted for, confirming the robustness of the process outcomes.

4. Conclusions

This work presents a novel De-Production model and a preliminary systematization of the D-Strategies in relation to the R-Strategies or R-Imperatives of Circular Business Models. In nowadays urgent situation regarding Climate Change impacts, high levels of pollution, record levels of materials extraction and energy use, companies must face new approaches to deal with these complex challenges. A systematic use of D-Strategies in articulation to Rs, namely the more commonly adopted 9R framework, can provide an instrumental strategy and support Design Departments, connecting with Design-for-X (DfX) disciplines and guidelines (e.g. Design-for-Disassembly,-Dematerilization,-Demanufacturing, etc.) for products, systems and machines design or redesign. Production Systems high level of optimization must be more and more translated into end of use-phase strategies to extend product or components lifetime or even as powerful solutions to unblock more circularity levels in product end-of-life, passing from a “Linear Economy booster” into a “Linear Economy attenuator”. The proof-of-concept via discrete simulation model proved to be an effective tool for understanding the De-Production processes by accurately modelling the flow and outcomes of various R-strategies. It allows for data-driven insights that enhance decision-making, enabling companies to evaluate different product conditions and adapt their strategies to maximize resource recovery and operational efficiency.

Despite the findings and contributions, a set of limitations can be described to this work, and recommendations extracted for future research. The addressed D-Strategies systematization touched only in a group of more used Ds with focus on mechanic/mechatronic products. Thus, future studies should enlarge the scope and compilation of D-Strategies, and also study other sectors applicability such as Construction and Buildings, Chemical products.

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