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Assessing the Role of Big Data and the Internet of Things on the Transition to Circular Economy: Part II

An extension of the ReSOLVE framework proposal through a literature review

Gustavo Cattelan Nobre*
COPPEAD Graduate Business School, Federal University of Rio de Janeiro, Rua Pascoal Lemme, 355 Ilha do Fundão, Cidade Universitária, Rio de Janeiro, RJ, 21941-918, Brazil

Elaine Tavares
COPPEAD Graduate Business School, Federal University of Rio de Janeiro, Rua Pascoal Lemme, 355 Ilha do Fundão, Cidade Universitária, Rio de Janeiro, RJ, 21941-918, Brazil

***Email:** gustavo.nobre@coppead.ufrj.br

This paper presents the main findings of a literature-based study of circular economy (CE) extending the technology attributes present on the Ellen MacArthur Foundation (EMF) Regenerate, Share, Optimise, Loop, Virtualise and Exchange (ReSOLVE) framework. The introduction and methods were presented in Part I (1). Part II concludes that there are 39 capabilities grouped into six elementary CE principles and five action groups, with public administration being the most interested sector, forming the CE information technology (IT) capabilities framework. It is expected the framework can be used as a diagnostic tool to allow organisations to evaluate their technological gaps and plan their IT investments to support the transition to CE.

1. Results and Discussion

For this study, a complete set of scientific publications was analysed. Regional and temporal characteristics are presented in **Figure 1** (from first publication to 2018; total of 226 documents, including articles, reviews, conference papers and proceedings, filtered according to remarks presented in the Methodology section of Part I (1)) and **Table I**. Europe and Asia lead the interest in the subject mostly due to the efforts and regulations established by the EU and China governments. North America (here including Mexico and other Central American countries), despite the high level of development of the geographies, occupies only the third place in publications, with less than 15% of participation. This number also draws attention to the fact the USA is one of the major environmental polluter countries according to the United States Environmental Protection Agency (US EPA) (2), which reveals a context of significant research opportunities for the region.

Considering all the publications, 53% came from scientific journals and 15 sources presented at least two publications on the subject. The *Journal of Cleaner Production* (ISSN 0959-6526) and *Sustainability* (ISSN 2071-1050) led with 19 and nine publications respectively, as shown in Appendix 1 (for all Appendices, see the Supplementary Information included with the online version of Part I (1)). The high number of other source documents (47%), along with the publication concentration in the past three years, may indicate science and academia are still in the early stages of development for the studied subjects.

The research also grouped publications according to the Standard Industrial Classification (SIC) codes (3). The majority of documents apply to public administration (32.3%), mostly because of smart city initiatives and suggests governments are leading initiatives and sponsoring research. A considerable number of publications (30.1%)

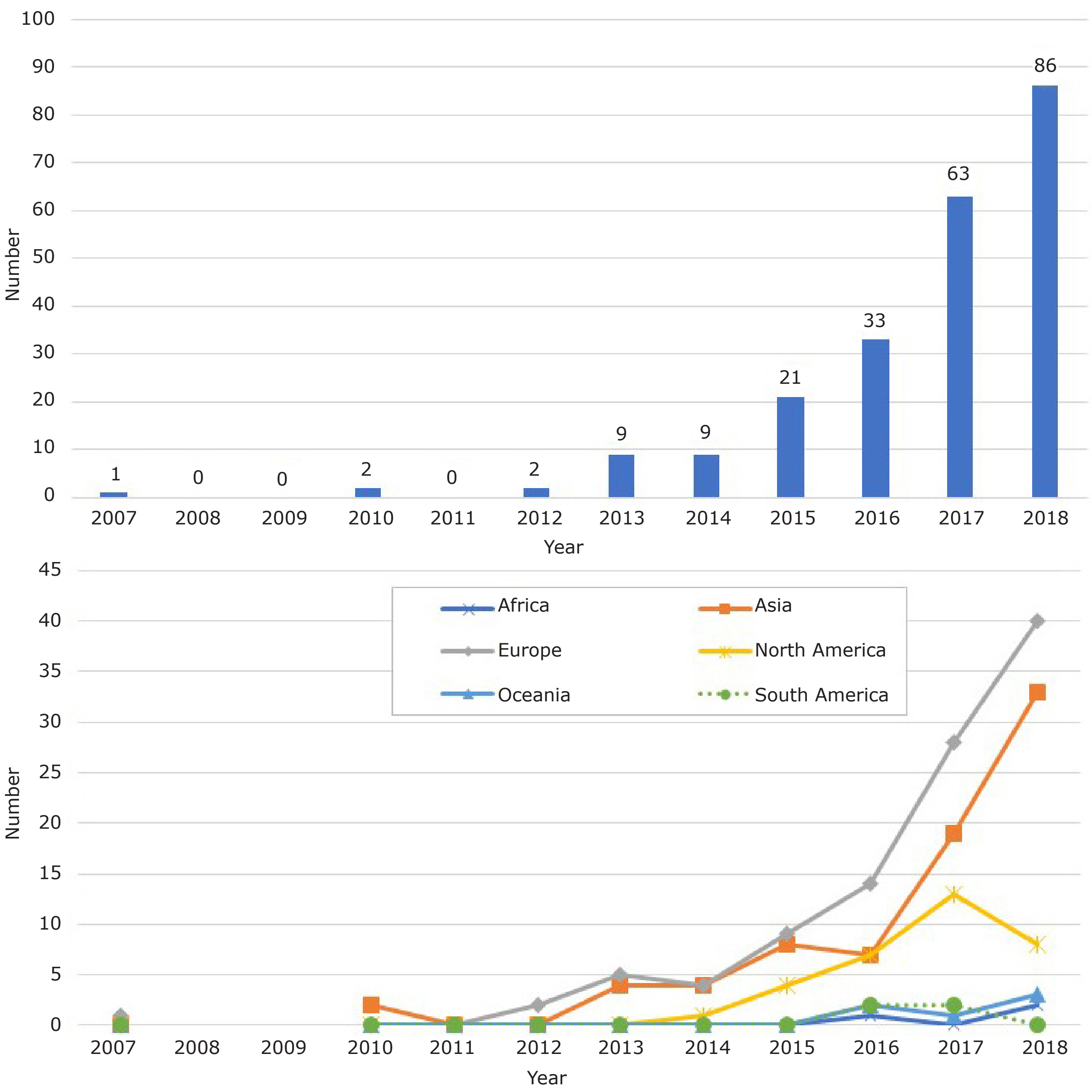

Fig. 1. Publication profile on CE and big data or IoT by region, total of 226 documents

Table I Detailed Publication Profile on CE and Big Data or IoT by Region, Total of 226 Documents

Region	All Years	2007	2010	2012	2013	2014	2015	2016	2017	2018
Africa	3	0	0	0	0	0	0	1	0	2
Asia	77	0	2	0	4	4	8	7	19	33
Europe	103	1	0	2	5	4	9	14	28	40
North America	33	0	0	0	0	1	4	7	13	8
Oceania	6	0	0	0	0	0	0	2	1	3
South America	4	0	0	0	0	0	0	2	2	0
TOTAL	226	1	2	2	9	9	21	33	63	86

were not allocated to a specific SIC code as they could not be related to any specific industry. Results are presented in **Table II**.

Documents were also grouped by methodology type, which demonstrates more interest in model development and reviews as shown in **Figure 2**.

Table II Publications by Industry Type with SIC Codes

Industry	SIC Codes	Number of publications	%
Public Administration	91–99	73	32.3%
Cross industry	n/a	68	30.1%
Manufacturing	20–39	18	8.0%
Construction	15–17	14	6.2%
Agriculture, Forestry, Fishing	01–09	11	4.9%
Transportation Equipment	37	8	3.5%
Business Services	73	7	3.1%
Private Households	88	5	2.2%
Engineering Services	8711	4	1.8%
Retail Trade	52–59	4	1.8%
Electric, Gas and Sanitary Services	49	3	1.3%
Transportation & Public Utilities	40–49	3	1.3%
Educational Services	82	2	0.9%
Mining	10–14	2	0.9%
Chemicals and Allied Products	28	1	0.4%
Computer and Office Equipment	357	1	0.4%
Food and Kindred Products	20	1	0.4%
Health Services	80	1	0.4%
TOTAL	–	226	99.9%

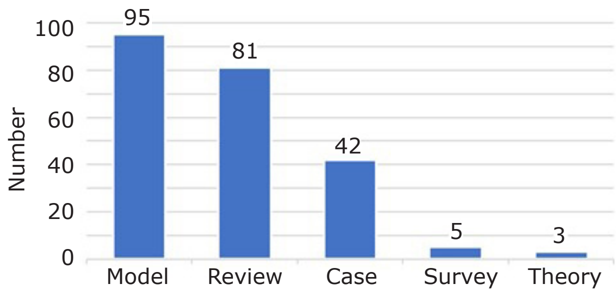

Fig. 2. Methodologies applied on 226 mapped documents

This indicates researchers have been putting more effort into standards, definitions, framework creation and reviews (which can be justified by the early stage of stability and maturity of the subjects). Other analysis was made according to CE principles (4) as demonstrated in **Figure 3**. The highest level of participation on the reduction principle suggests a major focus on changing consumer behaviour with the use of new technologies rather than investing in clean energy sources or extending product lifespans. On the other hand, the reclassification principle, despite its importance, still lacks technology efforts.

Supplementary details regarding mapped documents, such as top publishing institutions, journals and authors are available in Appendix 1.

In Appendix 8 we also present some practical case studies mapped during the literature review for distinct industries and countries in order to illustrate how CE can be fostered by big data and internet of things (IoT).

1.1 Content Analysis

Research extracted the 150 most frequent words from the 226-article text corpus in order to verify and confirm that the resulting capabilities list is

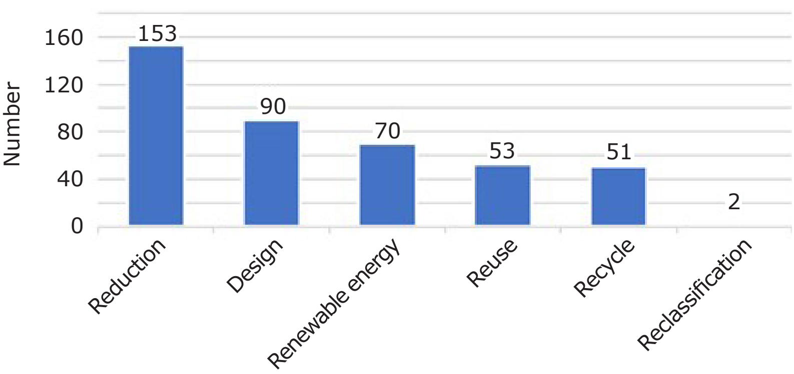

Fig. 3. CE principles identified in 226 mapped documents, some articles with more than one principle

addressing the most relevant topics. The word cloud generated is shown in **Figure 4**.

Bigram, trigram and four-gram generation proved to be a valuable insight resource as some compound expressions not only appeared in the top 150 list, but also performed as an important validation tool for capabilities generation (for example 'cloud computing', 'energy consumption' and 'smart sustainable city'), all key aspects of the validated capabilities list.

The top 20 expressions mapped are presented in **Table III**. The complete list of top 150 expressions is available in Appendix 4.

The words 'product', 'service', 'urban' and 'city' all appeared with high frequency, indicating initiatives for different industry types can benefit from big data and IoT, for example, and therefore influenced the framework development (i.e. specific treatment for industry type). The same analysis was made for each expression, performing essentially as a verification tool to ensure the framework and capabilities were consistent.

Fig. 4. Word cloud containing the 150 most frequent words from all 226 mapped articles

1.2 Experts Review

The first version of the resulting capabilities framework was submitted to a group of domain experts who provided useful insights into the study. **Table IV** shows the main contributions accepted from the domain experts. Typographic errors, rephrasing, use of synonyms and other small revisions are not listed.

The list of domain experts is presented in Appendix 2.

1.3 CE IT Capabilities Framework

The final framework resulted in a set of 39 capabilities divided according to the six CE principles and presented in **Figure 5** and **Table V**. It builds on both the ReSOLVE framework (5) and the six CE principles (4). The mapped capabilities were separated into application groups and industries, as some are considered technological tools, others new processes, some long-term projects and others punctual actions.

The mapping considering each capability and the corresponding block of the framework is presented in **Figure 6**. Capabilities not related to any industry are considered as applicable to any (cross industry).

1.3.1 Framework Highlights

The ReSOLVE Framework itself promotes a direct application of modern technologies on the elements 'optimise' (leverage big data and automation), 'virtualise' (dematerialisation) and 'exchange' (for example three-dimensional printing). With the establishment of the CE IT capabilities framework, not only can new applications be observed to those elements, but also it is now possible to notice that all elements of ReSOLVE can benefit from cutting-edge technologies. For example: the 'regenerate' element can be leveraged with net metering and the use of solar energy allows the use of IoT

Table III Most Frequent 20 Expressions and Frequencies

Expression	Frequency	Expression	Frequency	Expression	Frequency
product	5658	**design**	3352	**challenge**	1470
energy	4894	**system**	3287	**source**	1466
process	4278	**power**	3187	**technical**	1463
develop	4241	**city**	3036	**monitor**	1450
service	3745	**urban**	2984	**measure**	1413
environment	3601	**operation**	2811	**strategy**	1395
time	3575	**local**	1481	**–**	–

Table IV Domain Experts' Main Contributions

CE principle	Contribution	Contributing expert[a]
Design	Clarification on urban areas relation to public administration only	3, 4
	Added ISO 20400 - sustainable procurement (applies to reduction, reuse and recycle principles as well)	1
Reduction	Process postponing: inclusion of 'no effectiveness loss' condition	5
	Decentralised offices: only if proven to provide more efficient use of available resources	4, 5
	Added emissions monitoring	4
Reuse	Added marketplaces for sourcing, value and managing reusable materials	1
Recycle	Added disassembling and remanufacturing	4, 6
	Policies application rather than only having the policies documented	1, 4
	Use of electronic tags	1
	Added recyclable resin	1
Renewable energy	Net metering added to list	4
	Blockchain transactions added to list	2, 4

[a] The domain experts are identified in Appendix 2, Part I (1)

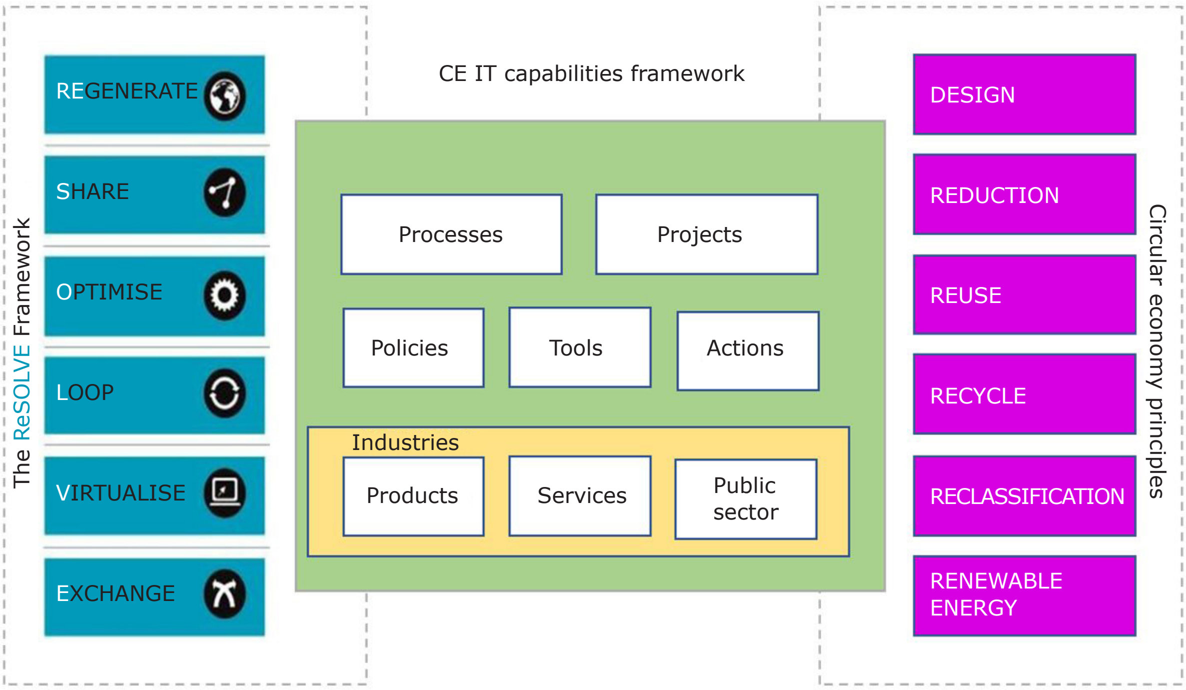

Fig. 5. The CE IT capabilities framework

based devices in remote areas, like agricultural crops; the 'share' element benefits from smart connected devices monitoring equipment's usage and providing predictive maintenance data and technology also connects users with similar interests allowing higher usage levels; in 'optimise', waste reduction can take many advantages from technology, varying from the use of AI and machine learning on product design to optimise resource consumption to application of green IT to increase product efficiency; 'loop' benefits from the use of AI to allow closing the loop on materials and to optimise waste collection and reverse logistics with IoT; 'virtualise' links directly with cloud computing

Table V Mapped Big Data or IoT Capabilities on CE Principles According to Literature Review

CE principle	Big data or IoT capabilities	Sample sources
Design (DS)	1. Parts made with compatible components with the support of modern technology based on artificial intelligence (AI), machine learning, big data or IoT that can be mixed after use without contamination for efficient recycling or upcycling or remanufacturing and designed for new uses, enhancing its after-use value 2. Use of big data or analytics during product design or conception to provide sustainable feedstock and optimised resource use to reduce waste generation during manufacturing processes 3. Product lifecycle management (PLM)[a] concepts supported by big data or IoT to improve product design, such as modular or replaceable components 4. Design and use of IT infrastructure for reuse or easy recyclability 5. Use of sustainable design criteria on technology selection processes, such as design for recycle 6. For public administration sector only: CE-planned urban areas designed and conceived according to smart city principles to optimise waste collection and value recovery with the use of IoT	(6–17)
Reduction (RD)	1. Minimise greenhouse gas and other pollutant emissions with the support of modern technologies such as analytics for monitoring and decision making 2. Optimise materials savings through smart connected devices 3. Use of decentralised IT technologies to provide resource use and consumption (either energy or components) reduction, such as cloud computing with big data, avoiding the need of robust local physical infrastructure 4. PLM concepts supported by big data or IoT to reduce waste generation and disposal 5. Use of smart sensors to monitor energy, water and other resource consumption in manufacturing processes 6. Use of smart sensors to monitor energy, water and other resource consumption within facilities of organisations 7. Machine behaviour monitoring to autonomously optimise energy, water and other resource consumption, even by postponing processes if necessary, without prejudice to process effectiveness 8. Use of IT devices and infrastructure in a way that offers minimal environmental impact (green IT) by optimising energy consumption 9. Use of technology-enabled decentralised offices and data centres proven to provide more efficient use of available resources (including human, for example no need to commute) 10. Use of energy savings or minimum waste generation criteria on technology selection processes 11. Energy efficiency improvement in data centres	(7, 12, 13, 16–28)
Reuse (RU)	1. Improve asset usage rates by applying CE business models such as leasing and 'platform as a service' (PaaS), enabled by IoT and big data 2. Product lifetime extension by using connected devices to facilitate predictive maintenance 3. PLM concepts supported by big data or IoT to improve product and component reusability 4. Product to service (possession *vs.* use) transition enabled or leveraged by IT to improve usability rates 5. Use of cloud-based marketplaces for sourcing, value and managing reusable materials 6. IoT-enabled waste collection or reverse logistics for materials (such as packaging) reuse 7. Monitor component location and quality in order to assess state and allow reuse 8. Use of IT devices or infrastructure in a way that offers minimal environmental impact (green IT) by reusing components to their maximum 9. Use of IoT devices to increase component sharing and reuse rates (such as in industrial symbiosis) 10. Policies for extending IT infrastructure lifecycle (for example, donation) 11. Use of product or component lifetime criteria on technology selection processes	(7, 9, 12, 13, 15–17, 25, 29–32)

(Continued)

Table V Continued

CE principle	Big data or IoT capabilities	Sample sources
Recycle (RY)	1. Apply AI to support 'closing the loop' on products and materials, allowing optimised product sorting and disassembly, remanufacturing and recycling 2. PLM concepts supported by big data or IoT to improve product recyclability 3. Use of IoT technologies to optimise waste collection and reverse logistics for recycling or upcycling, including the use of electronic tags on trash bins 4. Use of IT devices or infrastructure in a way that offers minimal environmental impact (green IT) by applying recycling policies 5. Use of IT infrastructure recycled from electronic waste 6. Applied policies for discarding obsolete IT infrastructure in a sustainable (for recycle) manner 7. Use of product recyclability (or made from recyclable resin) criteria on technology selection processes	(7, 9, 12, 13, 15–17, 25, 33)
Reclassification (RC)	1. Applying IoT integrated with AI to allow mixed industrial technical (non-organic) waste automated separation	(7, 34–36)
Renewable energy (RN)	1. Use of renewable energy sources (including light, motion, temperature) for IT devices to operate autonomously, mainly in poorly accessible remote areas 2. Power IT devices or infrastructure with renewable clean energy 3. Net metering-based[b] renewable energy generation, monitoring, consumption and selling (leveraged by blockchain when applicable)	(25, 37–43)

[a] Process of managing the entire production lifecycle from design, through engineering, manufacturing and ultimately service and usage
[b] Solution where consumers generate their own power and receive credits for the excess power they produce. Excess power is delivered to the grid, so net metering can be thought of as an energy storage solution that allows consumers to push and pull energy to and from the grid

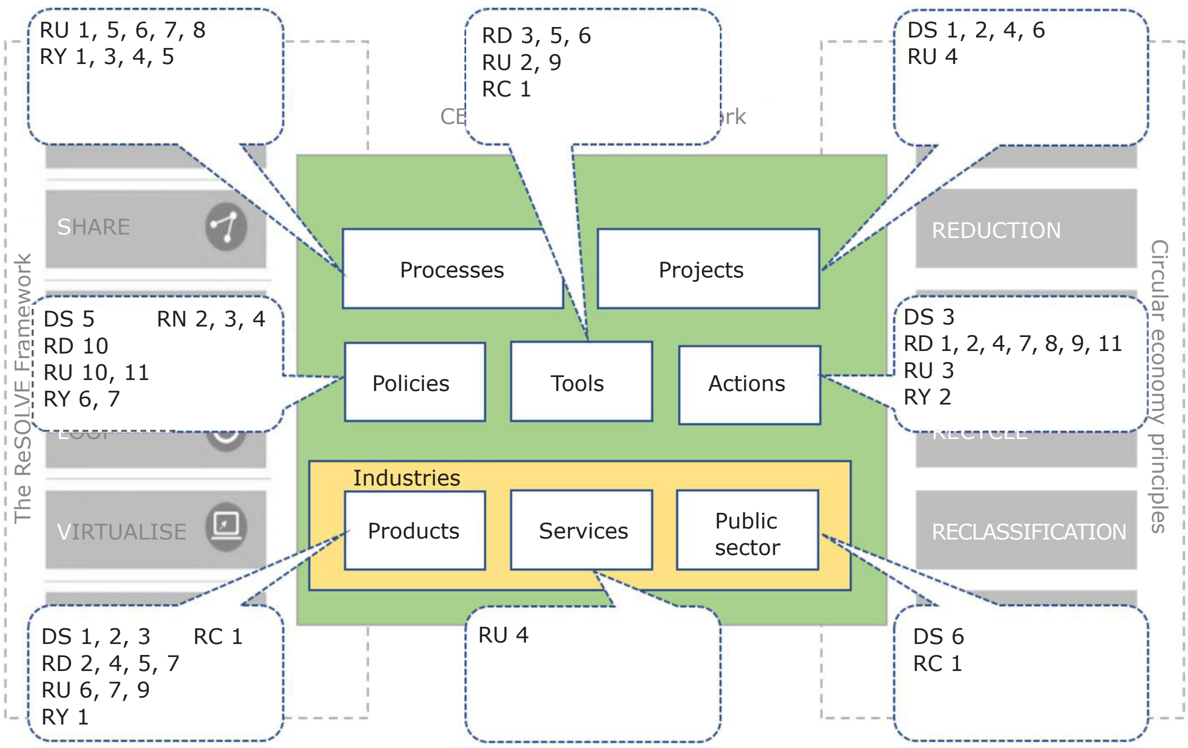

Fig. 6. The CE IT capabilities framework with mapped capabilities

and the home office; and 'exchange' may use technology on product design to promote shifting to renewable materials feedstock.

2. Conclusions

The scientific interest in applying modern technologies such as big data or IoT in the transition to CE is growing. Articles from 2017 and 2018 alone account for 66% of all the publications on the subject to date, reflecting what takes place in practice, given the number of cases and models identified – 60% of all articles mapped. Nevertheless, from the 21 different CE frameworks identified, only three mention IT as a component, and most of them refer to EMF as a primary CE reference, some built on EMF's ReSOLVE framework. Therefore, IT scientists, scholars and practitioners still do not have at their disposal a framework to be followed that would allow a technological gaps assessment. This framework development was the article's main purpose, which identified 39 IT capabilities necessary for organisations to consider themselves technologically circular.

The main scientific contribution of this study was the extension of the existing ReSOLVE framework to a level of detail that will allow IT professionals to assess their current CE gaps and plan their actions to enable an easier transition to CE. Additionally, the role modern technologies aligned with Industry 4.0 play in the organisational transition to CE was identified, and the status quo of related research around the world and the most interested institutions and publications were described.

In addition to the traditional literature review of 226 articles retrieved from Scopus® and Web of Science™ databases, the following triangulations were carried out to allow research confirmation and comprehensiveness: content analysis through statistical tool 'R', grey literature analysis and expert opinions. The capabilities were then divided according to the six CE principles presented in the literature: six for the design principle, 11 for reduction, 11 for reuse, seven for recycling, one for reclassification and three for renewable energies. The findings indicate that there are principles currently more susceptible to IT than others and that the public administration sector has attracted more research interest in the area possibly because of current initiatives fostered by government entities and agencies.

The following future research opportunities originate directly from this study: the conception of a scale with metrics to allow organisations to self-assess and benchmark (i.e. how many and which capabilities should an organisation implement and to what extent before it can be considered circular); and the confirmation of the framework's performance by applying it in the form of a questionnaire or survey against selected organisations of different ports and industries.

The limitations of the study lie mainly in the volatility of recent modern technologies that may not have a long lifecycle, making the framework obsolete in the short term. In addition, since it is an essentially theoretical study based on published documentation, it still lacks practical confirmation through organisational case studies.

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Appendices

The Appendices are in the Supplementary Information included with the online version of Part I (1).

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The Authors

Gustavo Cattelan Nobre holds a Bachelor's degree and MSc in Business Administration. He is a researcher and PhD candidate at COPPEAD Graduate Business School, Federal University of Rio de Janeiro (UFRJ), Brazil, with emphasis on big data and IoT. He also holds postgraduate degrees in Marketing and Corporate Finance and is a Systems Analyst. He is a professor at UFRJ and delivers postgraduate courses in the areas of administration, finance and project management. He is a reviewer for international congresses and journals and has more than 20 years of professional experience in the corporate world, most of them performing executive and project management functions in multinational consulting companies for large organisations in the areas of management consulting and IT. Certified Project Management Professional (PMP)®.

Elaine Tavares is Dean at COPPEAD. She was a post-doctoral researcher at the University of Texas at San Antonio, USA, and at the Centre d'Etudes et de Recherche en Gestion (CERGAM) of Université Aix-Marseille III, France. She received her DSc in Administration from Escola Brasileira de Administração Pública e de Empresas (EBAPE)/Fundação Getúlio Vargas (FGV) and her MSc in Corporate Management from EBAPE/FGV. She was a professor at University of Brasília (UnB) and at EBAPE/FGV. She is the leader of the topic big data and analytics in the Brazilian Academy of Management (ANPAD). She has more than 20 years' experience in large companies, especially in the financial and education sectors.

