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Risk management of Circular Economy: a framework based on Interpretive structural model

Roberta Pellegrino[a]*

[a]*Department of Mechanics Mathematics and Management, Polytechnic University of Bari, Via Orabona 4, 70126 Bari (Italy)*

Abstract

Over last years Circular Economy has attracted increasing attention from scholars and businesses, due to its ability to decouple the economic and social growth from the usage of natural resources and the degradation of the environment. Several risks however affect the CE adoption and implementation. In this regard, it is of paramount importance to identify the relationships between circular economy practices, the risks associated with them and their mitigation strategies in order to identify the drivers on which to act for an adequate and efficient transition. Through a review of the literature of main risks and the analysis of case studies, the Interpretive Structural Modeling (ISM) methodology has been used to discover these relationships in the Italian furniture industry. This is the first study of its kind which provides evidence about the adoption and implementation of CE practices and related risks in the furniture sectors as well as mitigation strategies which can be used to manage such risks and overcome such barriers. The outcome of this study will help companies operating in furniture industry as well as policy makers to devise strategies to favor an adequate and efficient CE transition.

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Keywords: Circular economy; Risk management; Furniture industry; ISM

1. Introduction and Research objectives

Due to growing environmental issues, related to the depletion of natural resources, pollution, climate change, and excessive waste production, in last years, companies, scholars and policymakers are working towards the development of economic models able to decouple the economic and social growth from the usage of natural resources and the

* Corresponding author. Tel.: +39-0805963897
E-mail address: roberta.pellegrino@poliba.it

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degradation of the environment. In this context, Circular Economy, namely, the industrial approach which is no longer based on the traditional linear “take, make, dispose” economic model, rather than on the circular cycles of “reduce, reuse, and recycle”, has attracted increasing attention from scholars, businesses and governments [1, 2]. The transition from a linear to a circular business model is necessary and fundamental to achieve the objectives of the Green Deal by 2050.

Despite the growing attractiveness of this alternative way to drive the economic, environmental, and social development, manufacturing industries still face several barriers to its full adoption [3]. Several risks and uncertainties affecting the CE practices implementation and adoption may hinder the full potential of this promising industrial approach [4]. This is particularly true for those industries characterized by a wide presence of small and medium enterprises (SMEs), which may suffer a scarcity of financial resources and skilled manpower to support this transition [5,6].

Furniture sector has a high potential to the transition towards circularity [7,8]. According to European Federation of Furniture Manufacturers (UEA) statistics, furniture waste in the EU accounts for more than 4% of the total municipal solid waste (MSW) stream [9]. About 10 million tonnes of furniture are discarded by businesses and consumers in EU countries each year, the majority of which is destined for either landfill or incineration.

Circular economy practices may contribute to counter these trends, since repair, refurbishment and remanufacture may foster value recovery, economic growth and job creation within the European furniture industry, while reducing resources consumption and saving the environment.

Italian furniture industry may act a pivotal role in this process, being one of the leading producers and exporters in the world [10].

Despite this potentiality, furniture industry shows a delay in adopting and implementing CE practices [11], which is also due to the lack of regulatory coordination at the EU, national and regional levels [12]. It was not until 2020 that the EU adopted an action plan. Only recently furniture industry leaders have shown a growing interest in circular economy. According to Federlegno Arredo, furniture companies are increasingly recognizing environmental sustainability as a major competitive advantage, as it encourages innovations that better meet consumer demand [12].

Thus, while the possibility of implementation and adoption of CE practices is immense in furniture industry, most of the companies in the sectors fall under the SMEs which have often scarcity and problems related to financial resources, information technology (IT) infrastructure, and skilled human resources and, hence, often perceive environmental sustainability as a cost factor [13].

It seems therefore clear that unless risks hindering CE adoption are identified and strategies to mitigate them are developed, the furniture industry will not be able to exploit the full potential of CE. As a consequence, it is crucial to investigate risks of CE adoption in furniture sectors and their mitigation strategies in order to identify the drivers on which to act for an adequate and efficient transition. This research contributes to this open issue by conducting a study which is the first of its kind providing evidence about the adoption and implementation of CE practices and related risks in the furniture sectors as well as mitigation strategies which can be used to manage such risks and overcome such barriers.

The outcome of this study will help companies operating in furniture industry as well as policy makers to devise strategies to favor an adequate and efficient CE transition.

The rest of the paper is organized as follows. In the next section the methodology adopted in the study is described. Section 3 presents main results and discussion. Finally, conclusion ends the paper.

2. Methodology

In order to analyze the interrelations between CE practices, risk factors and main mitigation strategies, interpretive structural modeling (ISM) has been used. This is a computer-based techniques which is able to graphically reproduce the real life complexity of the relationships between several factors.

The steps followed for the ISM approach are the following:

- **Step1**. Identify variables which have to be studied (i.e., CE practices, risk factors and mitigation strategies).
- **Step 2**. Establish the contextual relationships among variables
- **Step 3**. Develop a structural self-interaction matrix (SSIM)

- **Step 4**. Develop the reachability matrix from the SSIM and then derive the final reachability matrix after checking the transitivity.
- **Step 5.** Identify the level of partition from the final reachability matrix.
- **Step 6**. Develop the matrix impact cross multiplication applied to classification (MICMAC matrix) and the final digraph showing the interrelationships among variables.

Through a literature review a list of factors related to CE practices, risks and mitigation strategies have been identified. After checking them with experts from the furniture industry, the factors listed in Table 1 have been considered.

Table 1. List of factors related to CE practices, risks and mitigation strategies.

	Category	Description	Sources
CIRCULAR ECONOMY PRACTICES (R-imperatives)	**Recycle**	CEP1: Recycling waste produced in the production process	[14]
		CEP2: Recycling consumer waste products	[14]
	Recover	CEP3: Designing products that can be easily repaired/refurbished and/or easily disassembled and recycled	[14]
	Reuse	CEP4: Use of biodegradable/recyclable packaging and/or recycled packaging	[14]
		CEP5: Transfer/sale of waste products and by-products to other organizations (industrial symbiosis)	[14]
		CEP6: Reuse of by-products/recycled materials from other organizations (industrial symbiosis)	[14]
	Reduce	CEP7: Reduction of energy consumption and/or use of renewable energy sources	[14]
		CEP8: Reduction of raw material consumption	[14]
RISKS AND UNCERTAINTIES	**Operational Risks**	OP1: Circular Material Availability Risk	[4] [15] [16] [17]
		OP2: Difficulty in the selection of Experts who provide Circular Services	[4] [6] [7]
		OP3: Poor-Relationships between Supply Chain Partners Risk	[15] [19] [20]
	Financial and Economics Risks	FR1: Risk of Recycled Material Costs	[15] [16] [20]
		FR2: Investment Cost for Skill Development Risk and high upfront Costs Risk	[15] [20]
	Technical and Technological Risk	TR1: Inefficient Design Routes for Recovery Products Risk	[15] [16]
		TR2: Insufficient Durability and Longevity Risk	[4] [19]
	Market Risk	MR1: Consumer Perception Risk and Market Forecast Risk	[16] [18] [20]
		MR2: Risk of Market Competition with linear oriented companies and supply chain	[4] [16] [19] [21]
	Governamental Risks	GR1: Lack of Political Support and Incentives to Circular Economy	[15] [16] [20] [22]
MITIGATION STRATEGIES	**Sharing strategy**	S1: Collaboration and information sharing with stakeholders (suppliers, customers, governments and policymakers)	[4] [21] [23] [24]
	Control strategy	S2: Redesign of decision policies and procedures to optimize supply chain and logistics systems (es. Reverse logistics)	[4]
		S3: Technological tools and digitalization	[4] [25]
		S4: Multiple sourcing	[4]

Then, following the ISM procedure, the SSIM has been developed by interviewing the CEO of a leading company operating in the Italian furniture industry. It is a bigger company which can provide a successful example of CE practices implementation within their processes and organizations, thus supporting SMEs' CE transition.

Four symbols are used to indicate the direction of relationship between factors, with i being the factor on the raw and j on the column:

- V: factor i will lead to factor j.

- A: factor j will lead to factor i.
- X: factor i and j will lead each other.
- O: factors i and j are unrelated.

Table 2. SSIM Matrix.

	cep1	cep2	cep3	cep4	cep5	cep6	cep7	cep8	op1	op2	op3	fr1	fr2	tr1	tr2	mr1	mr2	gr1	s1	s2	s3	s4
cep1		O	A	O	O	X	X	X	V	A	O	O	V	O	V	O	X	V	O	O	A	O
cep2			A	A	O	A	O	O	A	O	A	V	O	A	V	V	O	X	X	O	A	A
cep3				O	O	X	O	V	X	A	A	A	X	X	V	V	X	A	A	X	A	O
cep4					O	A	O	V	A	A	A	A	O	A	O	V	O	O	O	V	O	O
cep5						O	O	O	O	O	A	A	O	O	O	O	O	O	A	O	O	O
cep6							O	V	X	A	A	A	A	A	X	X	V	A	A	V	A	A
cep7								O	O	A	O	O	V	O	O	O	V	A	O	O	O	O
cep8									A	A	A	A	O	A	O	O	V	O	A	O	A	O
op1										O	A	A	O	A	O	O	V	O	A	A	O	A
op2											O	O	O	O	V	V	O	O	A	V	A	O
op3												V	O	X	O	O	V	O	A	V	O	V
fr1													V	O	O	O	V	A	O	A	O	V
fr2														A	O	O	V	O	O	O	O	O
tr1															O	O	V	O	A	A	A	A
tr2																V	V	O	O	O	O	O
mr1																	V	O	A	O	A	O
mr2																		O	A	A	A	A
gr1																			O	O	O	O
s1																				A	A	O
s2																					A	X
s3																						V
s4																						

Starting from the SSIM matrix, after checking the transitivity, the final reachability matrix has been developed:

Table 3. The final reachability matrix.

	cep 1	cep 2	cep 3	cep 4	cep 5	cep 6	cep 7	cep 8	op1	op2	op3	fr1	fr2	tr1	tr2	mr 1	mr 2	gr1	s1	s2	s3	s4	**Driv. Power**
cep 1	1	1	1	1	0	1	1	1	1	0	0	1	1	0	1	1	1	1	0	1	0	0	15
cep 2	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	1	18
cep 3	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	19
cep 4	1	1	1	1	0	1	0	1	1	0	0	1	0	1	1	1	1	1	1	1	0	1	16
cep 5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
cep 6	1	1	1	1	0	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	0	1	18
cep 7	1	0	1	0	0	1	1	1	1	0	0	0	1	0	1	0	1	1	0	0	0	0	10
cep 8	1	0	1	0	0	1	1	1	1	0	0	0	1	0	1	0	1	1	0	0	0	0	10
op1	1	1	1	1	0	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	0	0	16
op2	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	19
op3	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	19
fr1	1	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	0	0	1	0	1	16
fr2	1	1	1	1	0	1	0	1	1	0	0	0	1	1	1	1	1	0	0	1	0	0	13
tr1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	19

tr2	1	1	1	1	0	1	0	1	1	0	0	0	0	0	1	1	1	0	0	1	0	0	11
mr1	1	1	1	1	0	1	0	1	1	0	0	0	0	0	1	1	1	0	0	1	0	0	11
mr2	1	1	1	0	0	1	1	1	1	0	0	0	1	1	1	1	1	1	0	1	0	0	14
gr1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	0	1	19
s1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	19
s2	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1	1	0	1	18
s3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	22
s4	1	1	1	1	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	18
Dep Power	20	19	21	18	9	21	10	21	21	2	8	15	18	16	21	19	21	16	13	18	1	13	

In the Step 5 of the ISM, the reachability matrix is partitioned in reachability, antecedent and intersection sets. The first set is constituted by the element itself and all other elements which are influenced or driven by the former. In the antecedent set there are the element itself and all other elements which influence or drive the former. Then, the intersection of reachability and antecedent sets is determined for all the elements. At the top-level of hierarchy there are the elements which have the same intersection and reachability set, which means that are those elements that are driven by other elements at the lower levels.

Once the top-level elements are identified, they are eliminated from the set of elements. then, the process is iterated until the bottom level, made by those elements that drive all the others.

Figure 1 reports ISM digraph.

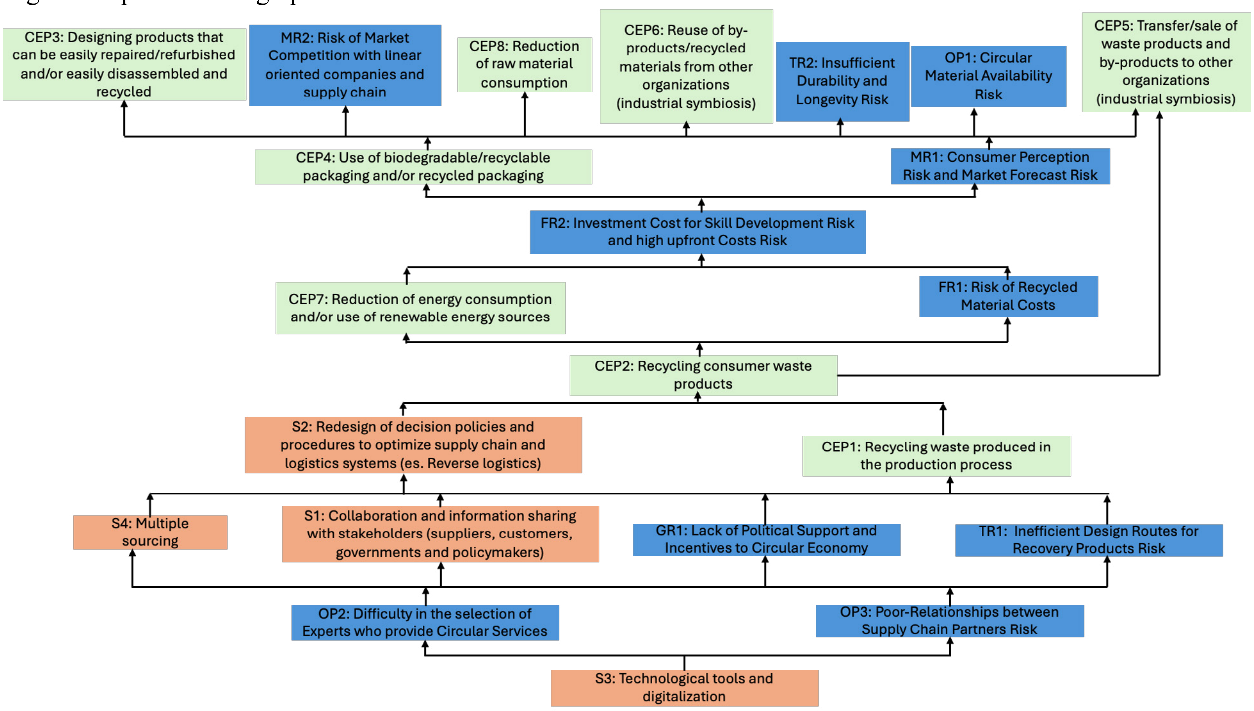

Fig. 1. ISM digraph.

Finally, the MICMAC analysis was performed, in order to identify the key variables. In particular, according to the driving power and dependence power of the elements, they were grouped in four categories, i.e., autonomous, dependent, linkage and independent (driver) (Fig.2).

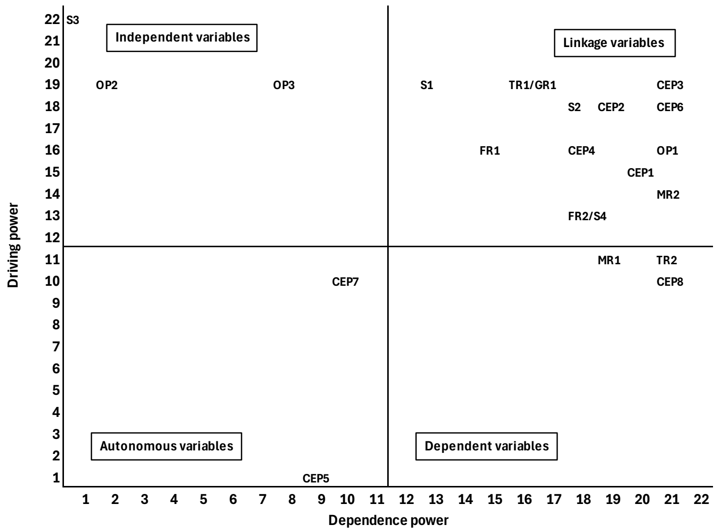

Fig. 2. MICMAC matrix.

3. Results and Discussion

Based on the ISM digraph and MICMAC matrix, it is possible to see that *Technological tools and digitalization* (S3) represents the **key strategy** driving CE application and implementation and mitigating operational risks (OP2 and OP3).

Difficulty in the selection of Experts who provide Circular Services (OP2) and *Poor-Relationships between Supply Chain Partners Risk* (OP3) are the **key risks** driving CE application and implementation.

Recycling consumer waste products (CEP2) and *Investment Cost for Skill Development Risk and high upfront Costs Risk* (FR2) are the **linkage elements** for CE practices implementation.

Based on the results, it is possible to notice that main lever driving CE adoption is characterized by the adoption of some strategic choices made by firms, namely, Technological tools and digitalization (S3).

Difficulties in selecting or researching experts to provide Circular Economy services (OP2) and Inefficient relationships between the partners of the Supply Chain (OP3) are the most important risks of CE.

By mitigating these risks, or otherwise positively influencing them, it is possible to act on financial risk and to improve the implementation of CE practices

We also find that the implementation of CE practices constitutes the top of the model, which then translates into a commitment and effort that must start from the management of other risks.

There is a kind of preference for and greater applicability of practices in the field of recycling.

4. Conclusions

This study investigates the relationships between circular economy practices, the risks associated with them and their mitigation strategies through the Interpretive Structural Modeling (ISM) methodology applied in the Italian furniture industry.

This is the first study of its kind which provides evidence about the adoption and implementation of CE practices and related risks in the furniture sectors as well as mitigation strategies which can be used to manage such risks and overcome such barriers. The outcome of this study will help companies operating in furniture industry as well as policy makers to devise strategies to favor an adequate and efficient CE transition.

The study is not without limitation. It is based on a single case study, which may limit the generalizability of findings. Further research may be devoted to considering multiple cases. Also, exploring CE practices in other industries, performong longitudinal studies to track CE adoption over time or comparative studies between different countries may be further research avenues.

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References

[1] ELLEN MACARTHUR FOUNDATIOS. (2015) The Butterfly Diagram: Visualising the Circular Economy. Available on: https://www.ellenmacarthurfoundation.org/circular-economy-diagram

[2] Dolci, V., Bigliardi, B., Petroni, A., Pini, B., Filippelli, S., & Tagliente, L. (2024). Integrating Industry 4.0 and Circular Economy: A Conceptual Framework for Sustainable Manufacturing. Procedia Computer Science, 232, 1711-1720.

[3] Upadhyay, A., Balodi, K. C., Naz, F., Di Nardo, M., & Jraisat, L. (2023). Implementing industry 4.0 in the manufacturing sector: Circular economy as a societal solution. Computers & Industrial Engineering, 177, 109072.

[4] De Lima, F. A., & Seuring, S. (2023). A Delphi study examining risk and uncertainty management in circular supply chains. International journal of production economics, 258, 108810.

[5] Maher, R., Yarnold, J., & Pushpamali, N. N. C. (2023). Circular economy 4 business: A program and framework for small-to-medium enterprises (SMEs) with three case studies. Journal of Cleaner Production, 412, 137114.

[6] Mura, M., Longo, M., & Zanni, S. (2020). Circular economy in Italian SMEs: A multi-method study. Journal of Cleaner Production, 245, 118821.

[7] Pellegrino, R., Russo, F., & Basile, L. J. (2024). The role of supply chain integration in the risk management of circular economy: a multiple case study in the furniture industry. Procedia Computer Science, 232, 2933-2940.

[8] Vejsiu, I., & Kola, E. (2024). Circular economy in wood processing sector, challenges, opportunities and solutions. Advanced Engineering Science, 4, 35-44

[9] UEA, Eco-label Furniture. Extension of the Scope. Final report. August 2004.

[10] Eurostat Prodcom statistics (https://ec.europa.eu/eurostat/web/prodcom) (accessed on 10 September 2024).

[11] Pellegrino, R., Russo, F., & Basile, L. J. (2024). The role of supply chain integration in the risk management of circular economy: a multiple case study in the furniture industry. Procedia Computer Science, 232, 2933-2940.

[12] FederlegnoArredo. Rapporto Ambientale 2010; FederlegnoArredo: Milan, Italy.

[13] Carissimi, M. C., Creazza, A., Pisa, M. F., & Urbinati, A. (2023). Circular economy practices enabling circular supply chains: an empirical analysis of 100 SMEs in Italy. Resources, conservation and recycling, 198, 107126.

[14] Reike, Denise, Walter JV Vermeulen, and Sjors Witjes. "The circular economy: new or refurbished as CE 3.0?—exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options." Resources, conservation and recycling 135 (2018): 246-264.

[15] Hassan, M. S., Ali, Y., Petrillo, A., & De Felice, F. (2023). Risk assessment of circular economy practices in construction industry of Pakistan. Science of The Total Environment, 868, 161418.

[16] Tuni, A., Ijomah, W. L., Gutteridge, F., Mirpourian, M., Pfeifer, S., & Copani, G. (2023). Risk assessment for circular business models: A fuzzy Delphi study application for composite materials. Journal of Cleaner Production, 135722.

[17] Mangers, J., Wieck, F., Nicolas, J., Plapper, P., & Löwer, M. (2022). Adaptive model to increase resilience for emerging supply chains within the circular economy–"Zirkelmesser" an innovative case study. Procedia CIRP, 107, 788-793.

[18] Choudhary, D., & Kumar, R. (2021). Risk investigation in circular economy: a hierarchical decision model approach. International Journal of Logistics Research and Applications, 1-26.

[18] AlMashaqbeh, S., & Munive-Hernandez, J. E. (2023). Risk Analysis under a Circular Economy Context Using a Systems Thinking Approach. Sustainability, 15(5), 4141.

[19] Dulia, E. F., Ali, S. M., Garshasbi, M., & Kabir, G. (2021). Admitting risks towards circular economy practices and strategies: An empirical test from supply chain perspective. Journal of Cleaner Production, 317, 128420.

[20] Moshood, T. D., Nawanir, G., Mahmud, F., Mohamad, F., Ahmad, M. H., AbdulGhani, A., & Kumar, S. (2022). Green product innovation: A means towards achieving global sustainable product within biodegradable plastic industry. Journal of Cleaner Production, 363, 132506.

[21] Jensen, S. F., Kristensen, J. H., Uhrenholt, J. N., Rincón, M. C., Adamsen, S., & Waehrens, B. V. (2022). Unlocking barriers to circular economy: An ISM-based approach to contextualizing dependencies. Sustainability, 14(15), 9523.

[22] Al-Awlaqi, M. A., & Aamer, A. M. (2022). Individual entrepreneurial factors affecting adoption of circular business models: An empirical study on small businesses in a highly resource-constrained economy. Journal of Cleaner Production, 379, 134736.

[23] Zheng, R., Huang, Z., Wu, Z., & Xie, G. (2022). Risk Control Simulation of Closed-Loop Supply Chain of Waste Electrical and Electronic Equipment Based on System Dynamics. Frontiers in Energy Research, 1288.

[24] Medici, P., van den Dobbelsteen, A., & Peck, D. (2020). Safety and health concerns for the users of a playground, built with reused rotor blades from a dismantled wind turbine. Sustainability, 12(9), 3626.